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The McGraw-Hill Magazine
of Nuclear Technology
with which is incorporated
Atomic Engineering and *Atomic Power*

Vol. 1, No. 4 : December, 1947

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NUCLEONICS

THE McGRAW-HILL MAGAZINE OF NUCLEAR TECHNOLOGY

Communication between Borderline Fields

THE LAST EDITION of the *World List of Scientific Periodicals* showed that over 33,000 different publications are now needed to record the monthly progress of the scientific world. Every scientist knows, however, that this rough measure of the ever-growing volume of technical literature does not mean that scientific investigation is becoming more specialized and divergent.

If we look on the investigation of nature as a gigantic jig-saw puzzle game being played by scientists of every specialization, we would see that every new scientific communication adds to the total picture and draws the players closer together. Each piece added to the picture suggests another gap that could be closed in a bordering area, and as the game proceeds the players are brought into closer contact and cooperation. Since nature is not static, but grows with the concepts and activities of the organisms it contains, our jig-saw puzzle never reaches completion; rather, it continually takes on new dimensions as the picture becomes clearer.

The last few decades in the history of nuclear physics illustrate how the addition of a new dimension to our understanding of nature accelerates all fields of science, and brings forth fundamental interconnections which shorten the intellectual distance between different fields of specialization.

Since no individual could possibly keep up with even a fraction of the volume of original research poured out monthly in the world's technical literature, the tradition of reviews and review journals has long been established for communication between borderline fields. The extraordinary enthusiasm and rate of progress now being shown on all frontiers of nuclear investigation, unpoisoned by secrecy, highlights the increasing value of periodic reviews as an essential supplement to the original literature.

The history of science tells us that it cannot advance any faster than the ability of its workers to keep up with each other. The individual experience of every working scientist confirms this, and it is recognition of this fact which leads him to regard the writing of reviews as a means of maintaining life in his own spheres of investigation.

—*W. M. D.*

Radiosodium as a Tool in Biological and Medical Research

Survey of investigations with radiosodium by a pioneer in clinical applications of nuclear radiations. Techniques and range of biological applications are described

By EDITH H. QUIMBY

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RADIOACTIVE SODIUM, Na^{24}, having a half-life of 14.8 hours and emitting penetrating beta and gamma radiations, has been found useful in a considerable number of biological and clinical studies. The purpose of this paper is to describe several of these, some from work in which the author has been involved, others from the literature. Most have been previously published in various journals; they are collected here to indicate the range of problems in which the isotope is valuable.

In living animals, sodium is uniformly distributed throughout extracellular body fluids, the sodium ion passing freely back and forth across capillary membrane. When radioactive sodium is administered by mouth or intravenously, it rapidly appears throughout the body. Since it emits penetrating radiation, its presence in a part of the body can be demonstrated by bringing near it a sensitive detector of radiation.

Typical Tracer Studies

Soon after the discovery of radiosodium, experiments were made to see how promptly the material, orally or intravenously administered, could be demonstrated in an extremity. Rates of excretion and deposition were studied in various organs and tissues. Such studies may be characterized as typical tracer studies, rather than as uses of radioactive sodium as a tool.

One of the first applications which might be characterized in this manner was the work of Kaltreiter and his associates at the University of Rochester in determining the volume of the extracellular fluid of the body. Measurements of this sort had previously been done with sucrose, sulfate, and thiocyanate, but none of these was entirely satisfactory.

Principle of Method

The principle is simple. Some hours after the intravenous administration of the test chemical, a sample of blood plasma is obtained and the concentration of the substance measured in it. Up to this time, all material excreted has been saved, and the amount of the test substance lost in this manner determined. Assuming that the material is uniformly distributed in extracellular fluid, the amount remaining in the body (the amount administered minus the amount excreted) divided by the amount per unit volume in the serum, gives the volume of fluid in which it is dissolved. Sucrose, sulfate, and thiocyanate each have drawbacks that do not exist with sodium.

Kaltreiter and his group and others made series of measurements in both normal and diseased subjects. They found in normals that about 21% of body weight is "sodium space" extracellular fluid, of which 15% is plasma

and 85% interstitial fluid. Repeated determinations on the same individual checked well, provided general health was maintained.

In patients with a disease producing serous effusion, concentration of radiosodium in pleural and ascitic fluid was essentially the same as in blood serum. In such patients the volume of extra fluid would be included in the extracellular volume determined by the use of radioactive sodium, and hence an estimate of the volume of excess fluid could be made by comparing the result with the normal for an individual of essentially the same weight. Especially advantageous in such a problem would be repeated measurements in the same subject.

Study of Shock Mechanism

Leading directly from this work is the study of Fox and Keston of Columbia University on the mechanism of shock from burns and trauma, as traced by radioactive sodium. Various clinical studies had indicated that in shock caused by extensive burns a redistribution of sodium and potassium took place. It appeared that the anti-sodium barrier between extracellular and intracellular fluids might have broken down. This could be tested with radiosodium by determining "sodium space" as just described. If this space is very much larger than normal and no commensurate increase in body fluid is indicated by edema, it is evident that the sodium is infiltrating tissues where it does not normally go.

In animal experiments, where shock was produced by a standard procedure, and analyses made with radiosodium, it was found that the burned tissues (skin and muscle, which normally contain very little sodium) did indeed take up a large proportion of the administered isotope. The consequence of such concentration in the damaged region would be a depletion of this electrolyte from normal parts of the body. If this were true, administration of an excess of isotonic sodium salt to the animal in shock should be remedial; this, in fact, was the case. Burned animals treated by intraperitoneal injection of normal saline equal to 16% of their body weight recovered, while similarly burned ones left untreated invariably died.

In humans with severe burns, the increase in "sodium space" together with the disappearance of sodium from the urine, indicated that the sodium was being withdrawn from normal equilibrium in extracellular fluid. In one case it was possible to demonstrate with a Geiger counter that the radioactive sodium deposited within a burned region was considerably greater than in the corresponding part of the uninjured limb. Successful treatment in this case and in similar ones was carried out by the administration of large volumes of isotonic (sixth molar) sodium lactate solution by mouth or infusion. It appears that replacing the withdrawn sodium together with extra water aids in re-establishing fluid balances, maintaining blood volume and blood pressure, and thus combatting shock.

In a preliminary series of cases, results show this type of treatment to be as satisfactory as with intravenous plasma, and of course the procedures are much simpler. A more complete report on a larger series of cases is promised but has not yet appeared.

Similar Study at California

A somewhat similar study is one by Greenberg and his associates at the University of California Medical School. It concerned the mode and rate of formation of cerebrospinal fluid. The key to the problem had been stated to be the role played by the tissue membranes separating the blood plasma and cerebrospinal fluid in the distribution of ions and molecules between these two

fluids. Questions were whether elements of the barrier membrane perform an active secretory function, whether the distribution of substances between the fluid and plasma is controlled only by passive diffusion, or whether these substances pass from plasma into extracellular fluid of brain and spinal cord and from these into spinal fluid. In the last case equilibrium would not be between plasma and spinal fluid, but between the latter and the extracellular fluid of the central nervous system.

Method Used

The study was undertaken by injecting various radioactive substances intravenously and determining their rate of appearance in the spinal fluid. Large dogs were used as subjects; after sodium pento-barbital anesthetization a cisternal puncture was done and all preformed cerebrospinal fluid withdrawn. Continuous drainage was maintained to collect the newly formed fluid. The radioactive material was then injected and its rate of appearance in the newly formed fluid obtained. Radiosodium attained equilibrium in extravascular fluid in these dogs in about an hour. It began to appear in the spinal fluid within a few minutes but did not reach plasma level for many hours. After 21 hours it was about 10% higher in spinal fluid than in plasma, as would be expected on the basis of their respective chemical compositions. Some elements showed a maximum in the cerebrospinal fluid, others did not. For all elements used, the ratio of concentration in spinal fluid to that in plasma took many hours to reach the values found in the stable state by chemical analysis. The delay was selective and varied greatly for different ions.

The authors concluded that the hindrance to the free passage of ions from the blood stream to the extracellular fluid of the central nervous system, and the deviation from the Donnan law of distribution of the steady ratios of the concentrations of these ions between the spinal fluid and the plasma, constitute evidence that the exchange between the blood and the brain takes place by a process of secretion and not by simple diffusion or ultra-filtration.

Experiments of the same general type were carried out by Visscher and his co-workers at the University of Minnesota to investigate movement of water and ions between intestinal lumen and blood, and by others to study transfer of ions across membranes in different body regions.

Velocity of Blood Flow

Radiosodium was used by Hubbard, Preston, and Ross to determine the velocity of blood flow in infants and young children. The material was injected into one antecubital vein and the time of its arrival at the opposite hand determined by a Geiger counter. Their series was small and the results were quite variable, but were at least as satisfactory as those obtained by other methods.

This use of the material readily suggests itself to anyone concerned with circulation times. Quite independently, similar studies were initiated by Smith and Quimby at Columbia University in connection with work on patients suffering from peripheral vascular disease. The material was injected into an antecubital vein. With the window of a portable shielded Geiger counter held against the sole of the foot, arm-to-foot circulation times were measured. After a small group had been tested, it seemed no valuable correlation between clinical condition and circulation time would be established. However, the work led to the development of a test which has proved very useful.

As equilibrium of radiosodium con-

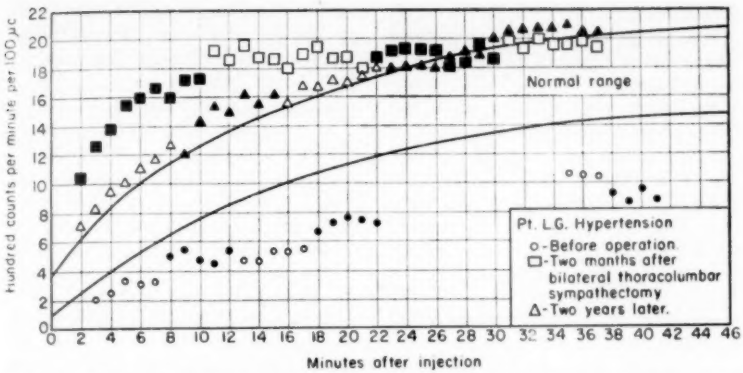

FIG. 1. Radiosodium "build-up" curves in a patient with severe hypertension relieved by thoracolumbar sympathectomy.

centration is built up between plasma and extracellular fluid, the counting rate of the Geiger counter at the foot increases, because the blood continues to bring sodium to the capillaries, where some of it diffuses out into the interstitial fluid and remains there. A curve can be plotted showing increase in counting rate with time after administration of the material. It has been found that the shape of this curve can often be correlated with clinical condition.

In individuals with no known vascular disturbance, the "build-up curves," calculated on the basis of 100 microcuries of radiosodium administered, all fall within the relatively narrow region indicated in Fig. 1 as "Normal Range." For patients with various vascular disorders, the curves may be within, above, or below this region. A very low curve may be attributed to arterial obstruction, arteriosclerosis, hypertension, spasm, degeneration of capillaries, or combinations of these factors (or others). A very high curve may be due to either inflammation (increased blood supply) or relaxation of vessel walls by nerve block, sympathectomy, or other reason.

Numerous illustrative curves have been published; some typical ones are shown in Fig. 1. In all these curves, solid symbols represent counts made against the right foot, open ones against the left. The chart shows data for a 40-year-old man with severe hypertension, relieved by bilateral thoracolumbar sympathectomy. The lowest curve (points indicated by circles) represents a test made before the operation. At this time the patient was unable to work and subject to very severe headaches. The two upper curves (squares and triangles) are for tests made two months and two years respectively after the operation. The patient's blood pressure is still rather high but he is symptom-free, and working at an active occupation.

Other hypertensives with very low pre-operative curves have responded to the operation in a similar manner. On the other hand, those with original curves in or near the normal range are not likely to show a high curve after sympathectomy, and they usually obtain little or no relief from the operation. The explanation appears to be that the very low curve is due, at least partly, to spasm, which is released by

the operation. On this basis, it is sometimes possible to foretell whether this operation should be beneficial in a particular case.

Similar studies have been carried out for patients with various disturbances of the peripheral vascular system. They have been useful aids to the medical staff in diagnosis, prognosis, selection and evaluation of therapeutic measures in arteriosclerosis, hypertension, thrombo-angiitis obliterans, Raynaud's disease, frost bite and other conditions. In cases of gangrene where the initial curve is low, indicating poor blood supply and little probability of healing, amputation is indicated. Formerly many such amputations were done above the knee because there was no way of being sure at what level the blood supply became adequate. With radiosodium and the counter, good blood supply below the knee can often be demonstrated, permitting a mid-calf amputation. This conservation of the knee-joint is of considerable economic and psychologic value.

In early work with a certain type of drug therapy, it was found desirable to cut off circulation from the extremities for a few minutes after injection of the material. For this purpose, blood pressure cuffs were applied close to the trunk and inflated to 250 mm of mercury pressure. In order to determine the efficiency of such a tourniquet in different types of individuals, radiosodium "build-up" studies were made by Quimby and Karnofsky similar to those already described for vascular diseases.

A tourniquet was applied to one leg in the usual manner, the other being left free. Radiosodium was injected into an arm, with the counter at the feet. As would be expected, the build-up in the unblocked foot followed the normal pattern already established. In the foot with circulation checked by the tourniquet, various degrees of retardation were found, depending on the obesity of the individual and the amount of pressure applied. Fig. 2 shows curves for a very obese individual and a tall, rather thin one. Solid points are for the blocked foot, open ones for the unblocked one; the circles are for the thin patient and the squares for the stout one. In the former, no blood reached the foot until the pressure had been reduced to something between the systolic and diastolic; it then came rapidly. For the stout patient, it was evident that a better type of pressure cuff must be devised.

In an investigation of mechanical methods of artificial respiration, it was desired to know whether blood could be made to circulate by a mechanical respirator if the heart had ceased to beat but blood coagulation had not occurred. Pulmonary ventilation alone is not sufficient to produce resuscitation, particularly if the circulation has

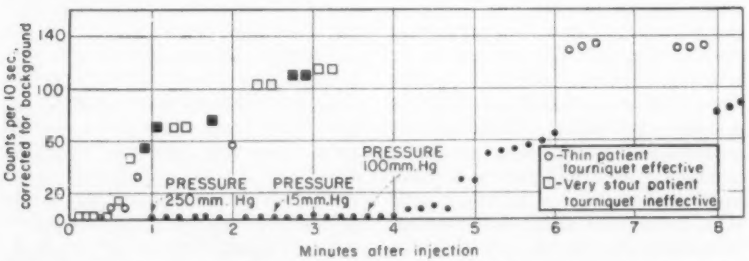

FIG. 2. Radiosodium "build-up" curves in patients with tourniquets applied to the upper thigh. Closed symbol, blocked foot; open symbol, unblocked foot.

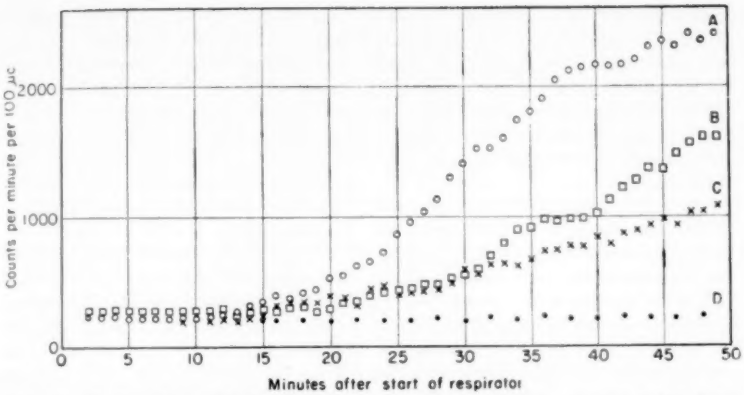

FIG. 3. Radiosodium "build-up" curves demonstrating movement of blood by artificial respiration in dead but heparinized dogs. *A*. Respirator using alternate pressure and suction; *B*. Suction alone; *C*. Pressure alone; *D*. No respirator.

stopped. Oxygenated blood in the lungs is of no value unless it can be moved out and transported to the vital centers of the nervous system. The question can be answered by introducing a tracer substance into the vascular system of an animal immediately following its death by asphyxiation, and recording any movement of this substance during the application of the resuscitative procedure. Such an investigation was carried out by Thompson, Quimby, and Smith using radiosodium as the tracer.

Dogs were anesthetized and an intravenous injection of heparin administered to prevent clotting of the blood. An endotracheal tube with occlusion cuff was inserted and clamped off, and the animal was allowed to succumb to obstructive asphyxia. About half an hour after clinical evidence of death, a small quantity of radiosodium was injected into a femoral artery or vein (separate studies were made for the two), the counter placed over the carotid-jugular region, and the resuscitator started. After a period of artificial respiration which varied with the type of apparatus used, radiosodium arrived in the vessels under the counter, and continued to increase in amount there as long as the count was followed—from 30 minutes to an hour. In animals with no respirator, or with no heparin, the material was never demonstrated above the diaphragm.

It was thus proved that the resuscitative procedures did circulate the blood, and that passive diffusion played no significant part. Fig. 3 shows curves for four of the animals, with three different respirators and with none.

At the end of the resuscitative efforts, the animal was autopsied, and blood taken from various regions was tested for the presence of the radioactive isotope. It was found in both chambers of the heart and in large veins and arteries throughout the body, but not in uniform concentrations. In the living animal, within less than a minute after injection the sodium content of the blood taken from any of the larger vessels is the same, because of the complete mixing after a few passages through the heart.

It has been concluded from this work with dogs that, when artificial respiration is employed in asphyxia, the ad-

ministration of heparin to prevent clotting should increase the possible recovery time of the patient by making it possible to move oxygenated blood even after the heart has stopped beating, although the movement will be slow and the oxygen content not uniform.

Penicillin in an aerosol administered by means of a nebulizer has been found useful in some cases of lung abscess, certain bronchial infections, asthma, etc. In the study of a number of problems concerned with its administration, it appeared that radiosodium might be an aid, since the vehicle for the penicillin is normal saline. By placing the shielded counter over various parts of the lungs immediately following the inhalation of an aerosol containing radiosodium, relative activities could be measured. Problems for investigation included the relative effectiveness of various nebulizers, the importance of particle size, and the value of adding various substances to the aerosol. Determinations of penicillin levels in the blood had failed to answer these questions. Talbot, Quimby, and Barach developed a satisfactory method for making these tests, and did some preliminary studies. The work is being carried on by Barach and his group.

In congestive heart failure, sodium turnover and excretion cease to follow normal patterns. Burch, Reaser, and their associates at Tulane Medical School carried out extensive investigations along these lines, using sodium-24 (half-life 14.8 hours) for short-period studies, and sodium-22 (half-life 3 years) for cases which could be followed for two months or more.

In the short-period investigation, a good series of normals and of patients with illness other than heart failure were studied as well as those with con-

EDITH H. QUIMBY, Sc. D., is associate professor of radiology (physics), College of Physicians and Surgeons, Columbia University. Dr. Quimby's association with radiation physics started in the fall of 1919, when she went to the Memorial Hospital in New York as research assistant to Dr. G. Failla, who was just starting to develop the radiation research laboratory there. As the laboratory developed, she rose to the position of associate physicist. During many years there, she worked on a variety of problems concerned with the measurement of radium rays and X-rays, and with physical questions arising in connection with the clinical uses of these radiations. Much of her work was done in cooperation with members of the clinical staff of the hospital. She inaugurated a teaching program in radiological physics, which has become increasingly popular with radiologists and other interested specialists.

In 1943, she went with Dr. Failla to develop a new radiological research laboratory at the College of Physicians and Surgeons. Almost immediately thereafter, she became affiliated with the Manhattan Project on a part-time basis. This division of time between the AEC and the university continues.

She has given many invited lectures and published about seventy papers and parts of several books. Her awards include the Janeway medal of the American Radium Society, the gold medal of the Radiological Society of North America, and the medal for scientific achievement of the International Exposition of Women's Arts and Industries.

gestive heart failure. Immediately following intravenous injection, blood and urine samples were taken every few seconds for three minutes, and then at gradually increasing intervals for three hours. In some cases edema fluid and sweat were also collected. As was to be expected, the sodium started to diffuse out of the circulation immediately, the plasma concentration never reaching the value it would have if all the sodium remained in the blood for any appreciable time. It appeared within less than a minute in the urine and in 75 seconds in sweat (in a patient studied in a hot and humid room).

From the curve of values for plasma concentration, it was possible to develop expressions for rates of diffusion of sodium across the vascular bed. These indicate that in the normal subject, about 32% of the total plasma sodium diffuses out of the blood every minute; of course, under equilibrium conditions, an equal amount diffuses back in. This leads to the astonishing figure of about 50 pounds of sodium chloride diffusing across the vascular wall daily in a 160-pound man. In cases of congestive heart failure, with great increase in volume of extravascular fluid, diffusion rates are still more rapid. On the other hand, the rate of sodium clearance by the kidneys is much less in the heart failure patients than in the normals.

Use of Sodium-22

In the study with sodium-22, a few normals and patients with congestive heart failure were followed intensively for two months. Daily measurements were made of weight, venous pressure, salt and water excretion, and sodium clearance. Patients suffering from congestive heart failure increased in weight because of the increasing volume of body fluid. These patients also retained sodium to a much greater degree than normal. Patients recovering from this condition eliminated both water and sodium faster than normal. Venous pressures varied concordantly with weight. Increasing diet sodium markedly increased excretion in the normal, without noticeably affecting the recovering heart-failure patient. Administration of a mercurial diuretic resulted in transient increase in water and sodium elimination, the latter being relatively greater.

The mechanisms connected with sodium and water retention in congestive heart failure have not been explained by this study, but it does appear to show that increase in intracapillary hydrostatic pressure is not responsible for the changes. Work presented to date is in the nature of a preliminary report.

Radiation Dosage

In all experiments using radioactive tracers, it must be assured that the accompanying amount of radiation is so small as not to constitute a danger to the subject, and not to influence the experimental findings. Marinelli has published a method whereby the radiation dose can be estimated for material administered and remaining within the body until its complete decay. On this basis, one microcurie of radiosodium per kilogram of body weight delivers a whole body radiation of about 0.11r over an effective period of about 2 days, when both beta and gamma rays are considered. The accepted tolerance dose for continuous irradiation is 0.1 r daily. Hence it is safe to use tracer doses of two or three microcuries of radiosodium per kilogram of body weight, and to repeat them a few times at reasonable intervals. *This dosage does not apply to any other radioactive isotope.* In most of the work described herein, doses have been of the order of 100 microcuries, which is usually less than 2 microcuries per kilogram.

The foregoing is a condensed account

of some uses of radioactive isotopes of a single element, sodium, as a tool in experimental medicine. It is not suggested that this covers the entire field of work with sodium; there is doubtless much more, both published and unpublished. As radioisotopes become more readily available, and their measurement somewhat simplified, it is expected that work of this type will become standard experimental procedure.

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"In the first two chain-reacting piles which were constructed at the Metallurgical Project (Argonne), neutrons were reproduced in a structure consisting of a lattice of uranium lumps embedded in a pile of graphite bricks. In this structure neutrons are reproduced in a cycle in which fast neutrons are slowed down to thermal energies by elastic collisions with carbon. Upon reaching thermal energies, the neutrons continue to diffuse without further loss in energy, on the average, until they are either absorbed in the pile or escape the pile by leakage. A fraction of the neutrons which are absorbed produce fission in uranium with the liberation of new fast neutrons. The average number of neutrons produced from one original neutron in such a cycle is called the reproduction factor, *k*. The value of *k* depends on the balance of neutron production, absorption, and leakage."

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RESEARCH WITH CARBON-14

(PART 2)

Second of two articles reviewing C^{14}-tracer problems, including synthesis of labeled molecules, application in organic chemistry, biochemistry and physiology, and safety precautions

By WARREN W. MILLER and T. DUANE PRICE*

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IN THE FIRST PART of this article,† the problem of synthesizing organic intermediates was introduced, and preparative methods for the most valuable intermediates were reviewed. This review is concluded below, and the subjects of biological and chemical research applications are discussed.

Other Isotopic Intermediates

According to the previously mentioned A.E.C. survey (see p. 16), several additional intermediates have been requested by two or more applicants. Most of these can be readily prepared from the intermediates whose preparation has been described or from some of the compounds used in their preparation.

$C^{14}H_4$ could be made by using the $C^{14}H_3I$ to give methyl Grignard reagent and reacting this with a compound containing acidic hydrogen. It can also be made directly from $C^{14}O_2$ using a culture of *Methanolbacterium Omelianskii* (*31*) or by direct hydrogenation of CO_2. Labeled ethylene was obtained by Du Vigneaud (*10*) in the following manner for his preparation of methionine:

$$CH_3I + HCN \rightarrow CH_3CN \rightarrow CH_3CH_2NH_2 \rightarrow CH_3CH_2N(CH_3)_3OH \rightarrow CH_2{=}CH_2 \quad (20)$$

It is apparent that if both labeled methyl and cyanide are used, a number of products containing the completely labeled ethyl group are obtainable from the ethylamine.

It is also obvious that the use of both labeled methyl and cyanide for double labeling of ethylene will usually be unnecessary, since it is symmetrical and would be obtained from either one alone at one half the specific activity possible by using both.

The above is an example of the multiple labeling that occurs automatically in a synthetic procedure that has a symmetrical intermediate containing the activity. In the case of intentional double labeling for the marking of two positions in a molecule, it is likely that better yields, based on the active intermediates, will be obtained by carrying out two syntheses to prepare the compound singly labeled in each place than could be obtained by using both active intermediates in the same synthetic procedure. The doubly labeled compound is then obtained by mixing these two in the desired ratio.

Isotopic carbon monoxide has been prepared in 99% yield by T. I. Taylor (*32*) by passing $C^{14}O_2$ over hot zinc. With small samples, the gas is heated in a closed vessel with the zinc for five hours.

Synthesis of C^{14}-Labeled Organic Compounds

Table 3† has shown some of the syntheses possible with the more important C^{14}-labeled intermediates. Naturally many other possibilities exist. Par-

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† NUCLEONICS, November, 1947

ticularly versatile are the biological syntheses. These include microbiological, botanical and tissue culture methods. While a detailed discussion of isotopically labeled compounds is not in order, the work which has been done with C^{14} will be briefly covered. Reference is made to Kamen (*9*) for syntheses previously accomplished with C^{11}. While no comprehensive summary of C^{13} syntheses appears to exist, the treatises of Buchanan and Hastings (*33*) and Wood (*34*) with their numerous references provide a fair coverage. The A.E.C. survey gives a list of compounds that have been labeled with C^{13}. The synthetic work done with C^{14}, already in this very early stage of its history, gives conclusive evidence of the remarkable versatility of this valuable isotope. Some of the more important and complicated organic syntheses with C^{14} are discussed below.

The synthesis of 1, 3, 5, radiomesitylene by Grosse and Weinhouse (*35*) is of interest particularly since it is the only ring-labeled benzene derivative thus far reported. Starting with $C^{14}O_2$, the procedure was as follows.

$$C^{14}O_2 + CH_3MgI \rightarrow CH_3C^{14}OOH \rightarrow (CH_3C^{14}OO)_2Ba \quad 94\% \quad (21)$$

$$(CH_3C^{14}OO)_2Ba \xrightarrow{500^\circ C} CH_2C^{14}OCH_2 + BaC^{14}O_3 \quad 95\% \quad (22)$$

$$CH_3C^{14}OCH_3 \xrightarrow{H_2SO_4}$$

10% (23)

Recently (*36*) C^{14} has been introduced into the 9-position of phenanthrene using the reaction sequence of formula 24 on the next page.

Turner has recently published an ingenious procedure for introducing C^{14} into the 3- or 4-position of the steroid nucleus (*37, 38*). It has been used for the labeling of both cholestenone and testosterone in the manner shown in formula 25.

The labeled phenylacetate was prepared in 70% yield from $C^{14}O_2$ via the Grignard reaction and subsequent reaction of active acetyl chloride with phenol. If methyl active phenylacetate had been used, the activity would have been in the 4-position.

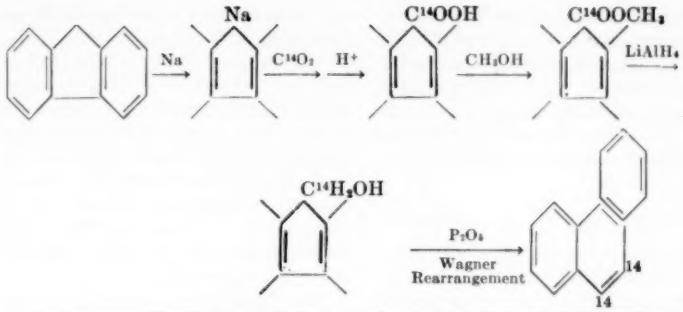
Heidelberger, Brewer and Dauben recently reported (*39*) a synthesis of the important carcinogenic compound 1,2,5,6 dibenzanthracene. Their preparation of the 9-labeled compound is summarized by the reactions shown in formula 26. The overall yield of the product, based on $C^{14}O_2$ was 11%.

Among the amino acids, at least four have been labeled with C^{14}. Loftfield (*25*) has prepared carboxyl-active glycine and alanine in 45% and 35% yields.* Reid (*40*) has synthesized β-active tyrosin in 19% yield, and methyl-labeled methionine has recently been synthesized in 50% yields (all yields based on $C^{14}O_2$).

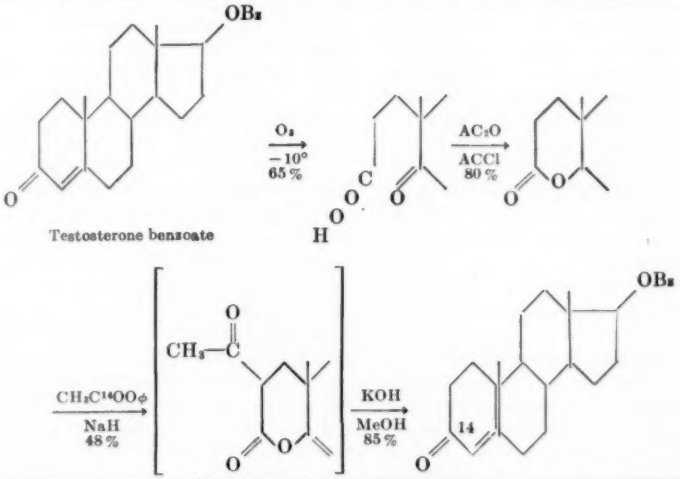
Skipper, et al. (*41*), recently described the synthesis of C^{14}-labeled ethyl carbamate (urethan). The A.E.C. survey lists several other compounds previously synthesized. Those not already mentioned or obvious include isobutane, prepared in 55% yield, guanidine hydrochloride in 66% yield, and benadryl in 43% yield. The "Report of a Symposium on the Use of Isotopes in Biological Research" lists a few additional syntheses, most of which are in the proposal stage as regards C^{14}.

Many complex organic compounds have been prepared biologically. From past results, it would appear that, unless methods are very carefully worked out, yields are low and dilutions high. Bloch's synthesis of C^{13} cholestrol (*42*) would, if C^{14} were used, give a sufficiently active compound for tracer

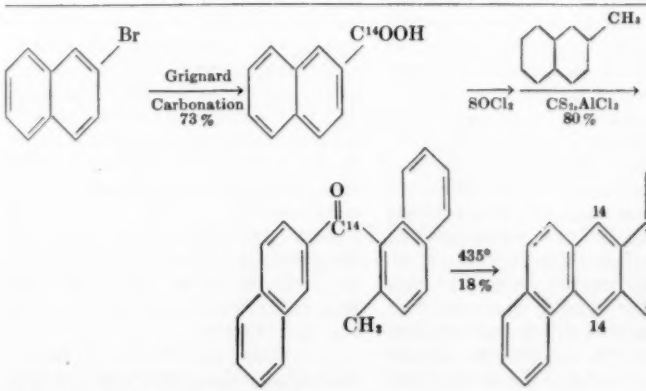
* Several previous workers had prepared carboxyl-labeled glycine (*10*).


Na
$C^{14}O_2$
H^+
$C^{14}OOH$
CH_3OH
$C^{14}OOCH_3$
$LiAlH_4$
$C^{14}H_2OH$
P_2O_5
Wagner
Rearrangement
14
14

(24)


OBz
O_3
$-10°$
65 %
AC_2O
ACCl
80 %
Testosterone benzoate
$CH_3C^{14}OO\phi$
NaH
48 %
KOH
MeOH
85 %
OBz
14

(25)


Br
Grignard
Carbonation
73 %
$C^{14}OOH$
CH_3
$SOCl_2$
CS_2,$AlCl_3$
80 %
C^{14}
CH_3
435°
18 %
14
14

(26)

studies. Recently, several important compounds have been isolated in high yield and activity from young barley plants grown in a $C^{14}O_2$ atmosphere (*43*). When biological syntheses are used, the distribution of isotopic carbon must usually be ascertained before the product is used.

RESEARCH APPLICATIONS OF C^{14}

A general survey of forseeable uses of radioisotopes has recently appeared in *Science* (*44*). C^{14} possesses more than average research utility because, for most purposes, it is the most conveniently used carbon isotope, and carbon occupies a pre-eminent position in all branches of biology and in many phases of chemistry and physics.

Biological Studies

The major biological studies using isotopic carbon, C^{11}, C^{13}, and C^{14}, may be grouped under the following general headings:

1. Photosynthesis
2. CO_2 metabolism (nonphotosynthetic)
3. Carbohydrate metabolism
4. Fat metabolism
5. Protein metabolism

Photosynthesis. Ruben, Kamen, Hassid, et al., attacked the problem of photosynthesis by studying the biological fixation of $C^{11}O_2$ in barley plants and in algae. Their prewar findings were published in a series of papers during the period 1939–1940 (*45*, *46*, *47*, *48*). Another early paper on photosynthesis is Frenkel's (*49*).

Now that C^{14} has become available, other groups are actively attacking this classical problem. Using barley and *Chlorella* as did the earlier workers, some have been able to make much more detailed studies due to the longer half-life of C^{14}. For example, they have shown that the five-minute dark uptake of $C^{14}O_2$ by *Chlorella* already equilibrated with CO_2 in the dark results in formation of succinic acid containing 70% of the activity (*50*). Using C^{11} in similar studies, the earlier workers had been forced to include succinic acid in the "water-soluble" component, as time was not available for purification and characterization of succinic acid and other compounds. Now a clear picture of the isotopic carbon distribution is possible with much improved chances of resolving photosynthesis mechanisms.

The distribution of C^{14} in photosynthesizing barley seedlings was recently reported (*43*). Also the distribution of C^{14} within the glucose from barley seedlings was exposed to $C^{14}O_2$ (*51*).

$C^{14}O_2$ Fixation. Literature on carbon dioxide fixation has already been well reviewed by Wood (*34*) who had, with Werkman, first demonstrated the nonphotosynthetic fixation of CO_2 by bacteria. Wood and his coworkers used C^{13} as a tracer.

Since publication of Wood's review paper, several other papers on $C^{14}O_2$ fixation have appeared. These include a study of $C^{13}O_2$ assimilation by fixation in the oxalacetate of pigeon liver (*51*) (and in dialyzed preparations, if Mn^{++} and adenosine triphosphate are added) and an investigation of the fixation of $C^{14}O_2$ into glycine and acetic acid during fermentation of uric acid by *Clostridium Cylindrosposum* (*52*).

Carbohydrates. Buchanan and Hastings (*33*) have provided an excellent review with 155 references on the use of isotopically marked carbon in the study of intermediary metabolism. Their paper places emphasis on carbohydrates.

Fats. Fat metabolism has been studied quite extensively with C^{13} and the literature has not been reviewed in any paper which stresses the application of isotopes.

Weinhouse, et al, studied the mechanism of ketone body formation from fatty

acids (*53*) and the reactions of carboxyl-labeled acetic acid to form acetoacetic acid in liver and kidney (*54*). Rittenberg and Bloch (*55*) used both C^{13} carboxyl and deuterium methyl-labeling to study the conversion of acetic acid to fatty acids in mice and rats. Buchanan, et al. (*56*), used C^{13} carboxyl-labeled acetic and butyric acids in fermentation studies.

Barker and his co-workers (*57*, *58*, *59*) have used C^{14} in a study of fatty acid metabolism of certain species of *Clostridium* and *Butyribacterium*. Kamen recently reviewed this work.

Amino acids, peptides and proteins. Several groups of workers recently began to investigate the protein problem with carbon-labeled tracer compounds. Shemin, continuing the Columbia group's N^{15} studies on intermediary protein metabolism, found that injected serine labeled with carboxyl C^{13} and amino N^{15} resulted in urinary hippuric acid in which dilution factors (referring to carboxyl and amide groups) for both isotopes were the same (*60*). The obvious conclusion was a confirmation of Knoop's β-oxidation theory, the serine being degraded to glycine which couples with benzoate to give hippuric acid. The Minnesota group (*61*, *62*) and some Swedish workers (*63*) have studied glycine metabolism in different species with C^{13}. Large-scale conversion of the glycine carboxyl carbon to $C^{13}O_2$ was noted in mice and *Torulopsis Utilis*, but not in surviving cat heart.

The metabolic lability of the methyl group in methionine has recently been demonstrated by the Cornell group using C^{14}-labeled methionine (*64*). Greenberg, et al., using C^{14}, recently provided further evidence that peptides are important intermediates in protein synthesis (*65*). The Harvard group (*64*) has used C^{14} to show that carbonate, when incorporated into liver slice proteins under certain conditions, resides almost exclusively in the carboxyl groups of dicarboxylic acids, particularly aspartic and glutamic acids. Others (*67*) have conducted preliminary study on the direct incorporation of labeled amino acids, especially alanine into tissue slice protein.

Chemical Studies

Very little work has been published so far on chemical investigations with C^{14}. One interesting study has been carried out (*68*) tracing the activity from carboxyl-active benzoic acid as it is in one case converted into phenyl acetic acid by the Arndt-Eistert reaction and then put through the Hoffman degradation, and in the other case converted into acetophenone and then carried through the Willgerodt reaction. This confirmed the work previously done on the Arndt-Eistert reaction with C^{13} (*69*), and the Hoffman degradation went as expected. The data indicate that the main product of the Willgerodt reaction, phenylacetamide, is formed without rearrangement of the carbon skeleton but that the phenylacetic acid formed at the same time is apparently formed by a different mechanism, since the carbon skeleton was rearranged. A very recent study (*70*) in the conversion of carbonyl-labeled acetophenone to phenyl glyoxal and then to mandelic acid has shown that there is no rearrangement of the carbon atoms in the side chain.

It is doubtful that C^{14} will find as much application in the investigation of organic rearrangements as might at first be thought. This is because of the extensive work that has already been done using structural homologues and the main result to expect from effort along this line is the confirmation of some highly probable mechanisms. In some other fields of chemical research, however, C^{14} holds much promise. The most obvious of these is heterogeneous catalysis, particularly

Results of A. E. C. Survey on C-14 Compounds

THE DATA PRESENTED in the following tables were obtained from 29 responses to a questionnaire which was circulated early this year to approved requesters of C^{14} by the Isotopes Branch, Atomic Energy Commission to determine quantities of C^{14} compounds desired in 1947 and 1948. One reply contained no estimates for 1947; 17 replies contained no estimates for 1948.

TABLE 1

Simple Organic Compounds Containing C^{14} Desired as Intermediates or Per Se during 1947 and 1948

No.	Compound	1947		1948	
		Quantity in terms of C^{14} content (mc)	*Number of requesters interested*	*Quantity in terms of C^{14} content (mc)*	*Number of requesters interested*
1.	CaC^{14}_2	6	2	20	1
2.	$BaC^{14}O_3$	?	1	2	1
3.	$NaHC^{14}O_3$	2	1	0	0
4.	$KC^{14}N$ or $NaC^{14}N$	21.6	8	23.6	3
5.	$HC^{14}N$	0	0	1	1
6.	$C^{14}H_4$ to C_8H_{18}	1.2	2	0	0
7.	$CH_3{\cdot}C^{14}H_3$	1	1	0	0
8.	$CH_3{\cdot}CH_2{\cdot}C^{14}H_3$	1	1	0	0
9.	$CH_3{\cdot}CH{:}C^{14}H_2$	1.5	2	0	0
10.	$CH_3{\cdot}C^{14}H{:}CH_2$	1	1	0	0
11.	$H{\cdot}C^{14}{\equiv}C^{14}{\cdot}H$	0.5	1	0	0
12.	$C^{14}H_3Br$	2	1	0	0
13.	$C^{14}H_3I$	14.4	8	4.6	2
14.	$C^{14}H_3{\cdot}C^{14}H_2Br$	2	1	0	0
15.	$C^{14}H_3{\cdot}C^{14}H_2I$	2.4	3	0.6	1
16.	$C^{14}H_2Br{\cdot}C^{14}H_2Br$	0.4	1	0.6	1
17.	$C^{14}H_2{\cdot}C^{14}H_2{\cdot}C^{14}H_2I$	4	1	0	0
18.	$C^{14}O$	1.1	2	0	0
19.	$C^{14}H_3OH$	13	2	20	1
20.	$C^{14}H_3{\cdot}C^{14}H_2OH$	3.1	2	0	0
21.	$HC^{14}HO$	0.4	1	0.6	1
22.	$CH_3{\cdot}C^{14}HO$	0	0	2	1
23.	$CH_3{\cdot}C^{14}OOH$	2	1	0	0
24.	$C^{14}H_3{\cdot}COOH$	2.1	2	10	1
25.	$C^{14}H_3C^{14}OOH$	3	2	0.1	1
26.	Br or $Cl{\cdot}CH_2{\cdot}C^{14}OOH$	1	1	0	0
27.	Br or $Cl{\cdot}C^{14}H_2{\cdot}COOH$	2	1	0	0
28.	Br or $Cl{\cdot}C^{14}H_2{\cdot}C^{14}OOH$	1	1	0	0
29.	$CH_3{\cdot}CO{\cdot}COOH$ (No C^{14} specified)	3	1	2	1
30.	$C^{14}H_3{\cdot}C^{14}OCl$	0	0	1	1
31.	$CH_3{\cdot}C^{14}OONa$	0.3	1	0	0
32.	$C^{14}H_3{\cdot}COONa$	1.0	1	0	0

TABLE 1 (Continued)

No.	Compound	1947 Quantity in terms of C^{14} content (mc)	1947 Number of requesters interested	1948 Quantity in terms of C^{14} content (mc)	1948 Number of requesters interested
33.	$HOOC^{14}{\cdot}C^{14}OOH$	0.1	1	0	0
34.	$HOOC{\cdot}C^{14}H_2{\cdot}C^{14}OOH$	0	0	5	1
35.	$C^{14}H_2(COOEt)_2$	5	1	20	1
36.	$HOOC{\cdot}CH_2{\cdot}\overset{\displaystyle OH}{\overset{\displaystyle \vert}{C}}{\cdot}CH_2COOH$ (No C^{14} specified)				
	$\overset{\displaystyle \vert}{COOH}$	0.1	1	0	0
		1	1	0	0
37.	$C^{14}N{\cdot}NH_2$	0	0	1	1
38.	$C^{14}H_2{\cdot}NH_2$	1	1	0	0
39.	$H_2N{\cdot}C^{14}{\cdot}NH_2$ $\quad\quad \Vert$ $\quad\quad NH$	1	1	0	0
40.	$CH_3{\cdot}C^{14}H_2{\cdot}C\vdots N$	1	1	0	0
41.	$C^{14}H_2{\cdot}CH_2{\cdot}C\vdots N$	0.5	1	0.1	1
42.	$R{\cdot}CHNH_2{\cdot}C^{14}OOH$	mg amts	1	0	0
43.	Tyrosine (No C^{14} specified)	mg amts	1	0	0
44.	Thyroxine (No C^{14} specified)	1	1	0	0
45.	Glucose (uniformly labeled)	0.2	1	0	0
47.	$(C_6H_5)_2{\vdots}C{\cdot}C^{14}H_2OH$	2	1	0	0
47.	$C_5C_{14}H_5OH$	0.45 mg	1	1.1 mg	1
48.	$C_6H_5{\cdot}C^{14}O{\cdot}C_6H_5$	0.45 mg	1	1.1 mg	1
49.	$C_6H_5{\cdot}C^{14}OOH$	0	0	10	1
50.	Benzoic acid (Ring C labeled)				
51.	3,4,5-tri-iodonitrobenzene (No C^{14} specified)	gm amts	1	0	0

TABLE 2

Synthesized Compounds Containing C^{14}

No.	Compound	Yield in C^{14} (%)	Quantity Re: C^{14} (mc)	Specific activity mc/mg C	Laboratory[1]	Available 1947[4]
1.	$C^{14}O$	99+	0.5	0.1	1	
2.	$(CH_3)_2{\cdot}CH{\cdot}C^{14}H_3$	55	0.09	0.00005	1	x
3.	$H{\cdot}C^{14}OOK$	90–95	0.9	0.1	2	
4.	$H{\cdot}C^{14}OOCH_3$	80–90	0.8	0.1	2	
5.	$C^{14}H_3OH$	75–85	0.75	0.01	2	
6.	$C^{14}H_3I$	70–80	0.7	0.01	2	
7.	Methionine[2]	50	0.47	0.0013	2	

(cont. on next page)

TABLE 2 (Continued)

Synthesized Compounds Containing C^{14}

No.	Compound	Yield in C^{14} (%)	Quantity Re: C^{14} (mc)	Specific activity mc/mg C	Laboratory[1]	Available 1947[4]
8.	$C^{14}N{\cdot}NBa$	95	—	—	3	
9.	Guanidine hydrochloride	66	0.66	—	3	x
10.	Nicotinic acid	30	—	—	5	x
11.	p-Aminobenzoic acid	—	—	—	5	
12.	$CH_3{\cdot}C^{14}OONa$	40	0.1	0.0058	10	
13.	Benzoic acid	85 (?)	0.38 mg	0.0005	11	
14.	Benzophenone	72 (?)	0.33 mg	0.0004	11	
15.	Benzhydrol	72 (?)	0.33 mg	0.00025	11	
16.	Benadryl	43 (?)	0.14 mg	0.0002	11	x
17.	$CH_3I{\cdot}C^{14}OOH$	55	—	—	12	
18.	$CH_2NH_2{\cdot}C^{14}OOH$	57	—	—	12	x
19.	$KC^{14}N$	70	—	0.007	15	
20.	Alanine	70	—	0.0001	15	
21.	$CH_3{\cdot}C^{14}OOH$	85	0.4	0.006	19	
22.	$CH_3{\cdot}C^{14}OOH$	50–60	—	—	20	
23.	$CH_3{\cdot}CH_2{\cdot}C^{14}OOH$	50–60	—	—	20	
24.	$CH_3{\cdot}CH_2{\cdot}CH_2{\cdot}C^{14}OOH$	50–60	—	—	20	
25.	$C^{14}H{:}C^{14}H$	—	—	—	22	x
26.	$C^{14}H_3{\cdot}C^{14}OOH$	95	0.2	0.003	26	x
27.	Glucose[14][3]	10–50	0.2	0.0003	26	x
28.	$C^{14}H_2{\cdot}C^{14}H_2{\cdot}C^{14}H_2{\cdot}C^{14}OOH$	90	0.01	—	26	x
29.	$C^{14}H_2{\cdot}C^{14}H_2{\cdot}C^{14}H_2{\cdot}C^{14}H_2{\cdot}C^{14}H_2{\cdot}C^{14}OOH$	90	0.01	—	26	x
30.	$CH_3{\cdot}CH_2{\cdot}CH_2{\cdot}C^{14}H_2{\cdot}CH_2{\cdot}COOH$	60–70	0.01	—	26	x

1 Laboratories involved are indicated by code number to reveal how widespread this research activity is. Laboratories 4, 6, 7, 8, 9, 13, 14, 16, 17, 18, 21, 23, 24, 25, 27, 28, 29 had not synthesized compounds containing C^{14}, but many of them are engaged in such work.

2 Name of compound is used in case the investigator did not indicate which C atom is labeled.

3 Apparently uniformly labeled.

4 Compounds marked "x" may be available in limited quantities. Further information obtainable from Isotopes Branch, Atomic Energy Commission, Oak Ridge, Tenn.

hydrocarbon catalysis. Very valuable results may be expected from the application of this tool to the study of alkylation, thermal isomerization, and such fundamental processes as dissociative absorbtion.

Other Applications

A very interesting study has been recently undertaken by Libby and his co-workers (*71, 72, 73*) on the natural occurrence of C^{14}. Cosmic radiations produce neutrons near the earth's surface at a small but finite rate. A fraction of these would be expected to disappear by reaction with nitrogen to produce C^{14}. Heavy carbon methane was separated from ordinary methane from different sources. These were largely $C^{13}H_4$, but $C^{14}H_4$, if present, would be even more greatly enriched in proportion than the $C^{13}H_4$ from the same material. These samples were carefully compared for their activity and it was found that there is about 10 dpm per gram carbon more C^{14} in methane obtained from carbonaceous materials on the earth's surface than there is in petroleum methane which has been stored for geologic periods

far from the neutron source. The interesting suggestion is now made by these workers that the age of a deposit of carbon containing material such as limestone, coal, or petroleum may be determined from the C^{14} content.

A possible future use of this isotope is in radiation therapy. The physiological effect of radiations of this type is known to be very similar to that produced by X-rays. The latter have long been used for the treatment of certain types of malignant growth. The use of radioactive isotopes for this purpose can offer the advantage of highly localized radiation without affecting the surrounding tissue when the uptake of the activity can be sufficiently specific.

The topic has received extensive investigation with two substances, radioactive phosphorus and iodine, which were known to be selectively absorbed by certain types of body tissue, and both have found specific application. The former is useful for the treatment of certain types of leukemia and the latter for some particular disorders of the thyroid. It is quite possible that, independent of any knowledge of the cause or the metabolic nature of abnormal tissue growth such as the malignant tumors, some substance will be found that is selectively absorbed by these tissues and it is reasonable to expect that this substance will be a carbon compound.

The radiation that will be available from this isotope can readily be calculated from the relation that 1 rep per day* is given by 0.3 μc C^{14} per gram of tissue. If the above hypothetical substance has a molecular weight of around 200 and contains one carbon labeled at the specific activity that is presently available, and the tissue can be induced to take up and retain one milligram of substance per gram of tissue, the radiation dosage would be about 30 rep per day, well within the range of therapeutic activity. While this is a lot of material to expect tissue to take up, it could be reduced by labeling more carbon atoms in the molecule, and if the results justified, even enriching the specific activity of the starting material by a factor of ten or greater. This estimate is based on utilizing C^{14} for therapy. Should the above hypothetical substance exist, it may well contain other atomic species which would make possible the selection of isotopes of a more desirable half-life and radiation than is available from C^{14}.

Safety Precautions

It is certainly desirable that something be said about safety precautions in working with C^{14} but the authors can say little that is very authoritative on this topic because of the present dearth of experimental evidence. From what can be calculated, C^{14} does not seem to be particularly hazardous. It emits no γ rays and only very weak β rays. Consequently quantities of C^{14} up to hundreds of millicuries in containing vessels of almost any sort will be quite safe to handle as far as external radiation is concerned. In quantities greater than this, the bremstrahlen will begin to be important. One millicurie of C^{14} fixed homogeneously throughout a 70-kg man will give a radiation dosage of about 50 millirep per day. Since one of the overall processes of biological metabolism is the oxidation of organic compounds and the elimination of the products, it might be thought that even the ingestion of small quantities of activity, especially as CO_2, might be relatively harmless but this attitude is unjustified because of several uncertainties. Many carbon compounds cannot be readily

* The *rep* is defined as that amount of radiation that delivers 83 ergs per gram of air or tissue (approx.), the same energy that is delivered to 1 gram of air by 1 roentgen of X- or γ radiation.

eliminated, and the activity may be concentrated in certain organs or metabolic cycles. The radiation dosage calculated above applies only to a distribution of the activity that is improbable. There is some evidence that appreciable fractions of activity initially as carbonate carbon may be fixed in the bone and retained over long periods (*74*).

There are several operating rules that seem reasonable on the basis of the known physical properties and uncertain metabolism of most C^{14} compounds.

1. Few precautions are necessary for protection against external radiation from moderate quantities of this isotope.

2. Any process carried out with more than a few microcuries of activity, in which it will at any time be gaseous, should be carried out in a hood even if done in a closed system because of the risks of breakage. Processes to be carried out with gaseous activities under pressure should be considered in the light of the capacity of the hood to handle an explosive emission of active gas. It should be remembered that most liquids and many solids have appreciable vapor pressures at room temperature.

3. Severe precautions should be taken to prevent getting activity as insoluble solids in the body by ingestion, inhalation, or puncture, because of the known difficulty the body has in handling such substances. The dusting of precipitates should be particularly watched.

An effort has been made in the preparation of this paper to acknowledge the source of experimental procedures and ideas where known but the authors would like to deny the inference of originality for those ideas not accredited. Many people are working in this field with a generally cooperative attitude toward passing along helpful information, and consequently the identity of the originator is frequently lost. The experience of W. W. Miller was gained largely while a member of Robley D. Evan's group at the Massachusetts Institute of Technology, and this is the source of much of the unacknowledged work. The advice and cooperation of R. W. Dodson in the preparation of this paper is also acknowledged.

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The formal use of a fifth coordinate in theoretical physics has been familiar to workers in the field of general relativity theory since the publication of Kaluza's unified theory of gravitation and electromagnetism. Indeed, the development of Kaluza's ideas by Klein, Pauli, Einstein, Flint, and others makes it difficult to see how a satisfactory unified theory could be developed without the introduction of an extra coordinate.

Within the framework of the special theory of relativity, the same device was used by Nordstrom to obtain a unification of his scalar gravitational theory with Maxwell electrodynamics, by Wilson and Cattermole in an attempt to explain classically the magnetic moment of the electron, and by Møller to derive a unified vector-pseudo-scalar theory of mesons.

The fact that we interpret events in terms of a framework of $(3 + 1)$ dimensions appears to lend to these theories a highly artificial character. The possible alternatives are

(a) none of these theories is valid,

(b) the use of the fifth coordinate is purely a mathematical trick,

(c) there is some deep significance in the extra space dimension, the awareness of which is denied to us because of our evolutionary background (e.g., predominance of gravitational forces over electromagnetic in determining the motion of macroscopic objects in our environment), and

(d) the extra coordinate is related to the proper time.

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PROPAGATION OF A CHAIN REACTION

NUCLEAR PRINCIPLES OF NUCLEAR REACTORS—II

Second of a series on the nuclear principles needed for the engineering design of chain-reacting systems. This paper treats the production, properties, and interactions of the neutron flux — with extensive references to the literature

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IN ADDITION to the types of absorption cross sections σ_a discussed in the first paper of this series (*1*), there are others of some importance in nuclear reactors.

Photofission

Sufficient excitation of the heavier nuclei by γ rays causes fission. The threshold energies E_f, and cross sections for uranium ($U^{238} + U^{235}$) and thorium (Th^{232}), have been determined by Haxby, Shoupp, Stephens and Wells (*2*) as:

$\sigma_a(\gamma,f)_U = 0.0035 \pm 0.001$ barns for 6.3 Mev γ's

$\sigma_a(\gamma,f)_{Th} = 0.0017 \pm 0.0005$ barns for 6.3 Mev γ's

$E_f(\gamma)_U = 5.4$ Mev;

$E_f(\gamma)_{Th} = 6.1$ Mev

Very few of the fission or fission-product γ rays are this energetic. This fact, together with the small cross section, accounts for the practically negligible importance of photofission in nuclear reactors.

Photoneutrons

Deuterium (H^2) and beryllium (Be^9) are among the few moderating elements suitable for thermal reactors. These elements also are the only ones susceptible to photodisintegration by γ rays of moderate energy. The binding energy of a neutron in H^2 is 2.18 Mev and in Be^9 is only 1.63 Mev. Accordingly, gamma quanta exceeding these energies may produce neutrons by photodisintegration of these elements. The cross sections $\sigma_a(\gamma,n)$ are quite small and increase only slowly with energy. Hence, the contribution to the neutron flux to be gained in a nuclear reactor by this process, while not negligible, is never greater than a fraction of 1%.

Yield of photoneutrons from the fission products of U^{235} in D_2O has been determined by Bernstein, Preston, Wolfe, and Slattery (*3*). The hard γ rays (> 2.18 Mev) are associated with eight fission products having half-lives of 2.5 sec, 41 sec, 2.4 min, 7.7 min, 27 min, 1.6 hr, 4.4 hr, and 53 hr. Of the photoneutrons, 85% appear in the two shortest half-lives, the 2.5-sec component being three times as intense as the 41-sec component. The total number of photoneutrons for an infinite amount of heavy water is estimated to be about 16.5% of the saturated delayed neutron activity. Assuming 1.0% delayed neutrons per prompt neutron (*4*), the maximum contribution from photoneutrons in D_2O would be about 0.17%.

Spatz, Hughes, and Cohn (*5*) have measured the photoneutrons produced both in D_2O and Be by the γ rays emitted by the fission products of U^{235}. They obtained an intensity of photo-

neutrons relative to delayed neutrons of 28%* for D_2O. With Be, a larger number of photoneutrons was observed, but the decay curve could not be broken down into discrete periods.

(n,2n)-reaction

In this process, which might be called neutron multiplication, the absorption of a neutron by a nucleus results in the release of two neutrons. From the energetics of the reaction, it is seen that the incident neutron must have a kinetic energy in the center-of-mass system in excess of the binding energy of the target nucleus for a neutron. Only the small proportion of neutrons in the high energy tail of the fission spectrum have sufficient energy to produce a $(n,2n)$ reaction in nuclei other than (H^2) and (Be^9). Hence, only in D_2O- or Be-moderated reactors is this reaction of importance. Since it requires fast neutrons, the contribution to the neutron flux is generally included in the fast effect ϵ(*1*, p. 33).

Inelastic Scattering

The Breit-Wigner relation for the elastic scattering cross section σ_s, given in equation 4 of ref (*1*), contained a term for the resonance scattering, plus a term for the potential scattering. In resonance scattering, a neutron coalesces with a nucleus, hence excites it by an amount equal to the sum of the binding energy, plus the incident kinetic energy of the neutron. The nucleus returns to its original ground state by emission of a neutron with the same energy as the incident neutron.† In potential scattering, a compound nucleus is not formed. Instead, the neutron wave is simply reflected at the surface of the nucleus. Although there may be differences in the phase shift of the scattered neutrons, both are elastic processes.

If the energy of the neutron is equal to, or greater than, that of the first excited level of the nucleus, inelastic scattering may take place, i.e., the compound nucleus may emit a neutron with less than the initial energy. After the neutron has left, the nucleus loses its residual energy by emitting one or more γ rays. Thus we see that resonance scattering is really just a special case of the more general process. However, in the theoretical treatment, resonance scattering is included in the expression for the elastic scattering cross section σ_s and inelastic scattering is included in the expression for the absorption cross section σ_a.

On the average, the energy of the first excited level is smaller, the heavier the nucleus. Light nuclei with four-shell structures, such as C^{12} and O^{16}, have first excited levels between about 4 and 6 Mev (*6*). Mg has its first excited level at 1.3 Mev (*7*), whereas heavy nuclei have first excited levels nearer 100 kev. Hence, inelastic scattering in general is negligible below an energy of about 100 kev. Above this energy, the scattering of neutrons is at least partly inelastic in the case of medium and heavy nuclei, such as Fe, Ag, Pb, and Bi. For high energy neutrons ($\gg$ 1 Mev) practically all the scattering is inelastic; what little elastic scattering there is goes mainly in the forward direction and is readily explained by shadow diffraction (*8*). Obviously, appreciable amounts of these elements cannot be used in fast reactors, i.e., reactors in which the neutrons cycle near fission energies. On the other hand, such elements should be particularly suited to resonance reactors, i.e., reactors in which the neutrons cycle at energies intermediate between thermal and fission. Pb and Bi are particularly interesting because of their unusually

* The photoneutron intensities were calculated from observed gamma-ray intensities.

† This discussion refers to a set of coordinates at rest with respect to the center of mass of the neutron and the nucleus.

small absorption cross sections over a wide range of neutron energies.

It is also evident that heavy elements are essential for γ-ray attenuation in reactor shields. If in addition these elements have large inelastic scattering cross sections, they also serve to knock down the fast fission neutrons to intermediate energies. Hydrogen is the most effective element for reducing the neutron energies the rest of the way to thermal values, where capture is highly probable. One of the complications is that, upon capture, γ rays are generally emitted (particularly the 2.18 Mev γ from radiative capture in hydrogen) and must be absorbed by additional heavy element shielding.

Elastic Scattering

This effectiveness of hydrogen in moderating the energy of neutrons is attributable to its large elastic scattering cross section and to its low atomic weight. As discussed by Bethe and Bacher (*9*), the large scattering cross section of hydrogen results from the dependence on spin orientation of the

GLOSSARY OF TERMS

D	= diffusion coefficient of thermal neutrons	B	= binding energy of a neutron in nucleus
E	= kinetic energy of neutron	p	= resonance escape probability in an infinite medium
E_f	= kinetic energy of fission neutrons	L	= diffusion length of thermal neutrons (in cm)
E_{th}	= kinetic energy of thermal neutrons	L_s	= slowing-down length (in cm)
$E_f(\gamma)$	= threshold energy for photofission	$\bar{r}_s^2$	= mean-square distance traversed by fast neutron (in cm^2)
∇	= vector operator del	$\bar{r}^2$	= mean-square distance traversed by thermal neutron (in cm^2)
σ_s	= cross section per nucleus for elastic scattering	η	= number of neutrons per fission
σ_a	= cross section per nucleus for absorption	k	= Boltzmann gas constant
σ_f	= cross section per nucleus for fission	ρ	= density of medium in gm/cm^3
λ	= $\lambda/2\pi$ = quantum mechanical wave length of neutron	s	= source density of neutrons
$\hbar$	= $h/2\pi$ = Planck's constant of action divided by 2π	T	= absolute temperature in °K
κ_0^2	= Laplacian of nuclear reactor	t	= time in seconds
M	= mass of nucleus	τ_0	= mean life of thermal neutron
n	= neutron density per cm^3	τ_f	= mean life for absorption to produce fission
v_0	= average velocity of thermal neutron in cm/sec	ξ	= mean logarithmic energy loss of a neutron per collision
φ	= scattering angle of neutron in center-of-mass system	ζ	= average number of collisions required to slow down a fission neutron
$\overline{\cos\Theta}$	= average cosine of scattering angle in laboratory coordinates	λ_a	= absorption mean free path (in cm)
r	= radial distance of neutron from center of nucleus	λ_s	= scattering mean free path (in cm)
A	= atomic weight of nucleus	λ_{tr}	= transport mean free path (in cm)
N	= number of nuclei per cm^3		

incident neutron and the scattering proton (H^1 nucleus). The binding energy B of the compound nucleus, in this case the deuteron, is 2.18 Mev (as previously cited) only when the spins of the two constituent particles are parallel (p state). If the incident neutron coalesces with the proton in the quantum state of antiparallel spins (s state), the amount of energy B' by which the nucleus is unstable is about 60 kev (*10*, p. 44), resulting in a high probability that the neutron will be scattered by the proton (*11*).

The scattering cross section $\sigma_s(H^1)$, based on very complete experimental observations over a wide range of energies, is shown in Fig. 1. Above an energy of about 10 Mev, $\log E$ (ev) = 7, the interaction is essentially independent of the relative spin direction. The cross section then increases with decreasing neutron energy E until at 10 kev it reaches a plateau value of about 21 barns which extends down to thermal energies. The explanation of this shape is evident from the approximate relation given by Bethe and Bacher (*9*) for the average cross section for the scattering of neutrons by protons:

$$\sigma_s(H^1) = \frac{\pi\hbar^2}{m}\left(\frac{1}{B' + E/2} + \frac{3}{B + E/2}\right) \quad (1)$$

where m = the mass of the proton or the neutron (considered equal for this purpose).

Chemical binding in hydrogenous materials causes a marked rise in $\sigma_s(H^1)$ below $E \approx 1$ ev. Fermi (*12*) has shown that the cross section is four times greater for protons strongly bound to an infinite mass than for free protons initially at rest. Sachs and Teller (*13*) have shown that this factor of four can be generalized for the scattering of neutrons by molecular gases if the neutron energy is great as compared to the energy differences of the rotational levels of the scattering molecule, but small compared to the quanta of molecular vibration. Bethe (*14*) has reviewed the effects of chemical binding. In addition to discussing the foregoing, he points out that the binding changes the angular distribution of the neutrons after scattering. The distribution is uniform (per solid angle) at small energies while no neutrons are deflected through more than 90 deg. by free protons. The low energy part of Fig. 1 is based on measurements of the scattering from paraffin ($C_{22}H_{46}$) corrected for the scattering by carbon, $\sigma_s(C) = 4.6$ barns.

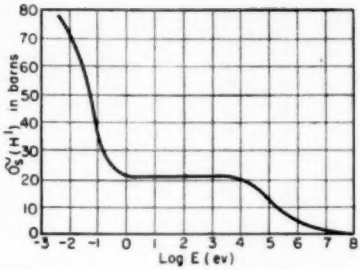

FIG. 1. Elastic scattering cross section of hydrogen (*17*)

The fact that the proton and neutron have nearly equal masses is also of importance in determining the moderating properties of hydrogenous materials. Condon and Breit (*15*) were among the first to consider in detail the energy distribution of neutrons slowed by elastic collisions, assuming isotropic scattering in the center-of-mass system. By a simple application of the conservation laws, it can be shown that the ratio of the neutron energy after a collision, to the neutron energy before a collision, is given by:

$$\frac{E}{E_0} = (1 - ax) \quad (2)$$

where $a = \frac{4mM}{(M+m)^2}$; $\cos\varphi = 1 - 2x$

m = mass of the neutron,

M = mass of nucleus,

TABLE 1

Nuclear properties of a number of substances of interest in nuclear engineering. Density ρ in gm/cm³ at 20° C (assumed = 1.0 for H_2 and O_2), atomic or molecular weight A (chemical scale), atoms or molecules per cm³ $N \times 10^{24}$, microscopic absorption and scattering cross sections σ_a and σ_s in barns per atom or molecule at $E_{th} = 0.025$ ev, macroscopic absorption and scattering cross sections $N\sigma_a$ and $N\sigma_s$ in cm^{-1}, absorption and scattering mean free paths λ_a and λ_s in cm, mean logarithmic energy loss per collision ξ, and the average number of collisions to slow down neutron from $E_f = 1.75$ Mev to value of E_{th} (as shown).

Substance	ρ	A	N	σ_a	σ_s	$N\sigma_a$	$N\sigma_s$	λ_a	λ_s	ξ	$\zeta(E_{th} = 0.025\ ev)$	$\zeta(E_{th} = 1.44\ ev)$
H_2	1.0	2.016	0.30	0.62	120	0.19	36	5.3	0.027	1.0	18	14
H_2O	1.0	18.016	0.033	0.62	124	0.020	4.1	50	0.24	0.971	19	15
D_2O	1.1	20.029	0.033	0.002	16	7×10^{-5}	0.53	1.4×10^4	1.9	0.567	32	25
Be	1.8	9.02	0.120	0.009	6.1	0.0011	0.73	910	1.4	0.203	89	69
BeO	3.0	25.02	0.072	0.011	10	0.0008	0.72	1250	1.4	0.170	110	82
Graphite	1.62	12.010	0.0805	0.0045	4.8	0.00036	0.39	2700	2.6	0.163	110	86
O_2	1.0	32.000	0.019	0.0032	8.2	6×10^{-5}	0.16	1.7×10^4	6.25	0.120	150	120
Na	0.97	22.997	0.025	0.50	3.5	0.0125	0.088	80	11	0.083	220	170
Al	2.7	26.97	0.060	0.23	1.5	0.014	0.090	71	11	0.070	260	200
Fe	7.9	55.85	0.085	2.5	11	0.21	0.93	4.8	1.1	0.035	520	400
Cu	8.9	63.57	0.084	4	8	0.34	0.67	2.9	1.5	0.031	580	450
Hg	13.6	200.6	0.041	425	15	17	0.61	0.059	1.6	0.010	1800	1400
Pb	11.34	207.2	0.0329	0.17	13	0.006	0.43	170	2.3	0.0096	1900	1500
Bi	9.8	209.0	0.028	0.016	9.2	0.0005	0.26	2000	3.8	0.0095	1900	1500
Th	11.5	232.1	0.030	6	~ 10	0.18	~ 0.30	5.6	~ 3.3	0.0086	2100	1600
U	18.7	238.1	0.047	~ 2	8.2	~ 0.1	0.39	~ 10	~ 2.6	0.0084	2100	1700

φ = the angle of scattering of the neutron in the center-of-mass system.

Thus, for $\varphi = \pi$, $x = 1$, and E/E_0 has the minimal value:

$$\frac{E_{\min}}{E_0} = 1 - \frac{4mM}{(M+m)^2} = \frac{(M-m)^2}{(M+m)^2} \quad (3)$$

For $m = M = 1$, which obtains for neutron* scattering on free protons, $E_{\min}/E_0 = 0$, i.e., the neutron makes a head-on collision and transfers all of its kinetic energy to the proton. Thus the maximum loss in energy of a neutron in a single collision is with a proton.* The minimal loss, of course, is zero. It has been established (*14*) that the geometrical mean $\overline{E}$ of these two extremes is the average residual energy of a neutron after a collision with a proton. Since

$$\ln \overline{E}(/E_0) = \int_0^{E_0} \ln (E/E_0) dE/E_0 = -1$$

$$\overline{E} = E_0/e \quad (4)$$

and after n collisions

$$\overline{E}_n = E_0/e^n \quad (5)$$

Hence, per collision, the decrease in energy in hydrogen is greater than in any other medium. The curves in Figs. 2 and 3, taken from Condon and Breit (*15*), emphasize this conclusion and afford a striking indication of how little the carbon nuclei in paraffin contribute to the slowing down of neutrons.

With a greater number of particles (nucleons) in the nucleus, both the spin dependence and the loss in energy per elastic collision are much less than for H^1. The scattering cross section of deuterium $\sigma_s(H^2)$ has been observed (*16*) to decrease monotonically from a value of about 3.5 barns at 0.35 Mev to 1.3 barns at 6 Mev. There is some evidence (*16*) for a small resonance at about 0.7 Mev which Marshak (*6*) has emphasized in his curve of the cross section. Oxygen shows moderate resonances at 0.45 Mev and 0.9 Mev and a possible doublet between 3.0 and 5.5 Mev (*6*, *16*, *17*). The resonances in the cross section for oxygen cause some irregularities in the cross-section curves of H_2O and D_2O as a function of energy. Of course, these are the most practical chemical compounds containing ordinary and heavy hydrogen for use as moderators in nuclear reactors.

As discussed in detail in a later section, carbon in the form of graphite offers a number of advantages as a moderator in nuclear power reactors. Hence, the scattering cross section of

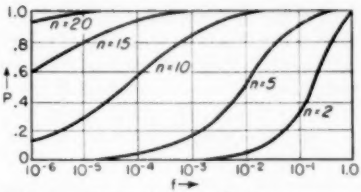

FIG. 2. The probability P that a neutron will have a fraction $\leq f$ of its initial energy after n collisions with protons (*15*)

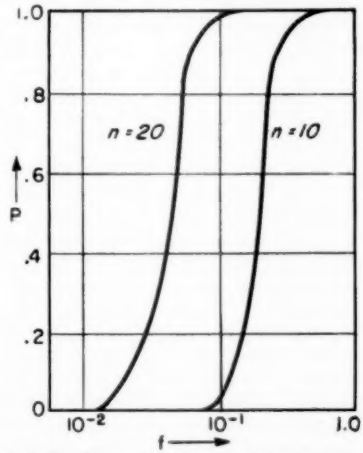

FIG. 3. The probability P that a neutron will have a fraction $\leq f$ of its initial energy after n collisions with carbon nuclei (*15*)

* Also with another neutron, a rare event indeed, even in high flux reactors

carbon has been studied very precisely over a considerable range of energies (*17* to *20*). With decreasing neutron energy, σ_s(C) rises from about 1 barn at 6 Mev to 4.6 barns at 10 ev, remains essentially constant down to 0.4 ev, then decreases in an irregular manner (because of crystal effects) down to about 3 barns at 0.03 ev. There is also a small resonance doublet between 3 and 5 Mev.

There are no inviolate generalizations regarding nuclear cross sections and no convenient periodic properties such as obtain for the atomic characteristics of the elements. However, in very general terms, nuclei can be grouped into three categories:* (*a*) For atomic weight $< \sim 100$, there are very few resonances for neutron energies $< \sim 100$ ev; (*b*) many resonances are observed for atomic weight 100 to 200, the average distance between resonances for a given nucleus being ~ 30 ev, but the resonances are distributed in a random manner; and (*c*) for atomic weight $> \sim 200$, most nuclei exhibit neutron resonances, with an average spacing of ~ 30 ev. However, there are striking exceptions, such as Bi, Pb, and Sn, in which no resonances have been observed up to 100 ev. Table 1 contains a number of average cross sections of particular interest in the general consideration of nuclear reactors that follows.

In addition to the absorption and scattering cross sections per nucleus σ_a and σ_s, sometimes called the microscopic cross sections, the density ρ and atomic (or molecular) weight A are included. These permit a direct computation to be made of the number of nuclei per cu cm (N) from the simple relation:

$$N = 0.602 \times 10^{24}\rho/A \qquad (6)$$

It is convenient to express N as a decimal fraction $\times 10^{24}$, because, when σ is in barns (10^{-24} sq cm), the exponents of 10 cancel in the products $N\sigma_a$ and $N\sigma_s$. These products are called macroscopic cross sections and are measured in $(\text{cm})^{-1}$. Hence, they are the equivalent of linear coefficients of absorption and of scattering. The reciprocals $\lambda_a = 1/N\sigma_a$ and $\lambda_s = 1/N\sigma_s$ are the mean free paths for absorption and for scattering, respectively, measured in cm. In the theoretical considerations of nuclear chain reactions which follow, both the macroscopic cross section and mean free path are used. Each is of value in visualizing different physical situations.

Slowing Down of Neutrons

Under the assumption of isotropic scattering, equation 3 indicates that E_{min}/E_0 equals the square of the ratio of the difference, to the sum, of the masses of the two particles which undergo elastic collisions. Hence, the atomic weights can be substituted in place of the masses. It is sufficiently accurate for our purposes to use the nearest whole numbers. Thus, for neutrons on nuclei of atomic weight A:

$$\frac{E_{min}}{E_0} = \frac{(A-1)^2}{(A+1)^2} \qquad (3a)$$

It is useful to define a quantity ξ which is the mean logarithmic energy loss per collision $(\overline{\ln E_0/E})$. The quantity ξ is easily obtained over the range E_{min} to E_0 from the mean-value theorem:

$$\xi = \frac{1}{aE_0}\int_{E_{min}}^{E_0} \ln\left(\frac{E_0}{E}\right) dE$$

$$= \frac{1}{aE_0}\Big[E\ln E_0 - E\ln E + E\Big]_{E_{min}}^{E_0} \qquad (7)$$

$$\therefore \xi = 1 - \frac{(A-1)^2}{2A}\ln\frac{A+1}{A-1} \qquad (8)$$

which for $A > \sim 10$ is given quite accurately by the approximation:

$$\xi = \frac{2}{(A + \frac{2}{3})} \qquad (9)$$

If the scatterer is molecular rather than

* This discussion is from Feld (*21*).

TABLE 2

Slowing-down length L_s (in cm) of neutrons in various substances (from Marshak). Except for the values for H_2O, which were calculated from an interval theory, values of L_s calculated from equation 23 using measured scattering cross sections are given for different initial energies E_f of the fission neutrons. In each case the indium resonance energy 1.44 ev, which is just above the top of the therma region, has been used for the lower limit E_{th}.

E_f (*Mev*)	ln E_f/E_{th}	H_2 (ρ = 1.0)	H_2O (ρ = 1.0)	D_2O (ρ = 1.1)	C (ρ = 1.6)	O_2 (ρ = 1.0)
3.0	14.55	0.728	6.4	10.5	19.2	56.8
2.0	14.14	0.608	5.3	10.1	17.7	48.8
1.0	13.45	0.463	3.8	9.7	15.9	42.2
0.50	12.76	0.375	3.1	9.4	14.7	38.6
0.20	12.06	0.328	2.7	9.1	13.9	37.9
0.10	11.15	0.293	2.4	8.8	13.2	36.8

atomic, ξ is computed as follows, using D_2O as an example:

$$\xi(D_2O) = \frac{2\sigma_s(D)\xi(D) + \sigma_s(O)\xi(O)}{2\sigma_s(D) + \sigma_s(O)} \quad (10)$$

Equations 8 to 10 were used to compute the values of ξ given in Table 1.

The product $N\bar{\sigma}_s\xi$, called the *slowing-down power*, is useful in comparing the moderating characteristics of materials. Since σ_s generally is energy dependent, the average value $\bar{\sigma}_s$ over the range from fission to thermal energy is often used. As discussed in the preceding section, hydrogen has the largest slowing-down power of any substance. For practical purposes, the hydrogen* is nearly always in chemical combination—e.g., as water, paraffin, or as a hydride or hydrate. While such hydrogenous mixtures have excellent slowing-down properties, they are particularly susceptible to decomposition by nuclear radiations (*22* to *25*). This limits their usefulness in power reactors.

Another parameter of fundamental importance in the propagation of a chain reaction is the *slowing-down length* L_s. Rigorously, L_s is defined in terms of the spatial moments of the neutron density in an infinite medium (*6*, p. 201). However, for present purposes it is sufficient to consider L_s† as given by the expression:

$$L_s = (\bar{r}_s^2/6)^{1/2} \quad (11)$$

where $\bar{r}_s^2$ is the mean-square distance that a neutron travels in being slowed down in an infinite medium through the energy interval considered (i.e., in thermal reactors, from fission energy E_f to thermal energy E_{th}). As a first approximation, L_s can be calculated from the relation for a homogeneous medium:

$$L_s^2 = \int_{E_{th}}^{E_f} \frac{\lambda_s\lambda_{tr}dE}{3\xi E} \quad (12)$$

provided the scattering and transport mean free paths λ_s and λ_{tr}, are known between E_f and E_{th}. Here λ_{tr} is the average distance in the incident direction that a neutron would travel after an infinite number of collisions. It is

* It is conceivable that liquid hydrogen might be useful as a combination moderator and working fluid in jet-propelled, nuclear-powered rockets.

† As given in equation 11, L_s^2 is identical with the *age* τ of the neutrons. The term *age* was introduced by Fermi because of the formal analogy between τ and the *time* t in the equation for heat conduction. The differential equation for the slowing-down density q in neutrons per unit volume per unit time which reach *age* τ is $\nabla^2 q = \partial q/\partial t$. The differential equation for the heat flow is $\nabla^2 T = k\partial T/\partial t$. A large number of solutions of the latter equation are known (*26*, *27*) for different geometries and boundary conditions.

readily shown (*28*), (*6*, p. 188) that

$$\lambda_{tr} = \frac{\lambda_s}{(1 - \overline{\cos\ \theta})} \approx \frac{\lambda_s}{(1 - \frac{2}{3}A)} \quad (13)$$

for $A >> 1$; $\overline{\cos\ \theta}$ = the average cosine of the scattering angle (in the laboratory coordinates) relative to the incident direction of the scattered neutron. As in the previous considerations, these relationships assume isotropic scattering in the center-of-mass system. For high energy neutrons, $E_f >> 1$ Mev, the contributions from higher angular momenta become appreciable, which results in anisotropic scattering. Under these conditions, ξ is also a function of energy.

Marshak (*6*, pp. 234–238) has computed values of L_s for various substances as given in Table 2. These data have been compared with values obtained by more rigorous methods. As is to be expected, the disagreement is greatest at the highest E_f. In each instance the approximate method of equation 12 gives low values of L_s. The difference is 16% in H_2, 12% in D_2O, 3% in C, and 9% in O_2.

The average number of collisions ζ required to slow down a fission neutron to thermal energy is obtained from the equation:

$$\zeta = (1/\xi) \ln E_f/E_{th} \quad (14)$$

Considering as averages $E_f = 1.75$ Mev and E_{th} as 0.025 ev, values of ζ for various substances are given in Table 1. In addition, values of ζ for $E_{th} = 1.44$ ev are included in Table 1 for use with Marshak's data on L_s given in Table 2.

Diffusion of Thermal Neutrons

After the fast fission neutrons have been slowed down by elastic collisions in the moderating medium, they have a statistical distribution of velocities determined by the thermal agitation of the nuclei. The neutrons can be considered as a gas, of very low partial pressure, dispersed in a very porous liquid or solid.* The degree of porosity is determined largely by the wave properties of the thermal neutrons (*1*, p. 28). For example, the mean free path of a thermal neutron (0.025 ev) in graphite is 2.9 cm which is about 10^5 times the mean free path of gas molecules at standard conditions.

The equation of continuity at a point can be written:

$$\partial n/\partial t = (\nabla \cdot D)\nabla n + s - n/\tau_0 \quad (15)$$

where: $\partial n/\partial t$ = the time rate of change of the thermal neutron density n.

s = the source density, i.e., the number of thermal neutrons produced per cu cm per sec.

n/τ_0 = the number of neutrons absorbed per cu cm per sec, τ_0 being the mean life of a thermal neutron with respect to absorption.

$\nabla \cdot D$ = the divergence of the diffusion coefficient D of thermal neutrons.

∇n = the gradient of the thermal neutron density.

In a homogeneous medium, at a uniform temperature, D is not dependent upon position, and the first term on the right in equation 15 can be written $D\nabla^2 n = D\Delta n$. Combining v_0 as the average velocity of thermal neutrons of mean life τ_0, mass m, and scattering mean free path $\lambda_s (\lambda_s << \lambda_a)$:

$$D = \lambda_s v_0/3 \quad \text{and}$$

$$v_0 = (8kT/\pi m)^{1/2} \quad (16)$$

where kT = the energy unit in the kinetic theory of gases.

In nuclear reactors, fission is the major source of neutrons.† These

* Even a thermal flux of 10^{12} neutrons per sq cm per sec is only equivalent to a pressure of 1.3×10^{-11} cm of Hg.

† As discussed in previous sections, (γ,n) and $(n,2n)$ reactions in Be and H^2 may contribute in a minor degree to the source density.

fast neutrons are soon slowed down by the moderator. This process constitutes the source term s. Since the fission rate is proportional to n and inversely proportional to the mean life for absorption to produce fission τ_f, the source density is given by:

$$s = (n/\tau_f)\eta \qquad (17)$$

where $(\eta - 1)$ is the net number of neutrons produced in each fission, since one neutron is required to induce the fission process.

Substituting equations 16 and 17 in equation 15, the time-dependent differential equation for the diffusion of thermal neutrons is obtained:

$$\frac{\partial n}{\partial t} = \frac{\lambda_s v_0}{3}\Delta n + \frac{\eta}{\tau_f}n - \frac{n}{\tau_0} \qquad (18)$$

A quantity known as the *diffusion length* $L \equiv (D\tau_0)^{1/2}$ is generally used in the calculation of the critical size of thermal reactors. It can be shown that

$$L = (\bar{r}^2/6)^{1/2} \qquad (19)$$

where $\bar{r}^2$ is the mean-square distance that a thermal neutron travels in an infinite medium before being absorbed. Thus L is analogous to L_s in equation 11. An approximate formula for the diffusion length is

$$L^2 = \frac{\lambda_s\lambda_a}{3} \qquad (20)$$

In a nuclear reactor at constant power, $\partial n/\partial t = 0$, and equation 18 can be written including L^2 as:

$$\Delta n + \varkappa_0^2 n = 0 \qquad (21)$$

where $\varkappa_0^2 = [\eta(\tau_0/\tau_f) - 1]/L^2$.

This relation has been derived in a slightly different manner and considered in somewhat greater detail by Friedman (*29*). The quantity $\varkappa_0^2 = -\Delta n/n$ is called the Laplacian of the reactor. It is a property of the medium in which the neutrons are produced and diffuse. As considered in later sections, $\varkappa_0^2$ is related to the critical size of a reactor through equation 21.

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Directory of Fundamental Nuclear Research

PRELIMINARY SURVEY

THIS LIST INCLUDES all of the basic nuclear physics research, under way or proposed, which has come to the attention of NUCLEONICS from various sources. Since the research directors mentioned have not provided the information directly or checked this copy, the accuracy of the listings cannot be guaranteed.

Despite the fact that some errors are thought to exist, NUCLEONICS is giving early publication to this preliminary listing because of its great immediate value for workers in the field. A more complete and detailed directory of unclassified research, including description and location of sources of nuclear radiations, is now under preparation.

PARTICLE ACCELERATORS

Now in Existence

Cyclotrons
- 15 in.—Cornell
- 16 in.—U. of Washington
- 26 in.—Collins, Rochester
- 27 in.—Stanford
- 27 in.—White, Princeton
- 28 in.—Pollard, Yale
- 32 in.—Siegbahn, Sweden
- 32 in.—Allison, Chicago
- 36 in.—Dunning, Columbia
- 37 in.—Kempton, Cambridge, Eng.
- 37 in.—Chadwick, Liverpool, Eng.
- 37 in.—Richardson, UCLA
- 37 in.—Lark-Horowitz, Purdue
- 38 in.—Biochemical Research Foundation, Newark, Del.
- 41 in.—Kruger, Illinois
- 42 in.—Pool, Ohio State
- 42 in.—Cork, Michigan
- 42 in.—Evans, MIT
- 45 in.—Kurie, Washington U. at St. Louis
- 45 in.—Mitchell, Indiana
- 47 in.—Allen, Pittsburgh
- 60 in.—Lawrence, Berkeley
- 60 in.—Tuve, Carnegie Institution
- 184 in.—Lawrence, Berkeley

Synchrotons
- 17 Mev—Fry, TRE, Malvern, Eng.
- 70 Mev—Pollock, General Electric

Betatrons
- 5 Mev—Fry, Ohio State
- 10 Mev high frequency—Charlton, General Electric
- 22 Mev—Kerst, Illinois
- 50 Mev biased—Charlton, General Electric
- 100 Mev—Charlton, General Electric

Deuteron linear accelerator
- ½ Mev—Cornell

Phillips generators
- 1 Mev—Devons, Cambridge, Eng.
- 1 Mev—Collie, Oxford, Eng.
- 1 Mev—Feather, Edinburgh, Scotland
- 2 Mev—Devons, Cambridge, Eng.

Electrostatic accelerators
- ½ Mev—Thomson, U. of London, Eng.
- ½ Mev—Talbott, Catholic U.
- 1 Mev—Inglis, Johns Hopkins
- 1 Mev—Tuve, Carnegie Institution
- 1 Mev—Van de Graaff, MIT
- 1.5 Mev—Fowler, Cal. Tech.
- 2 Mev—Mandeville, Bartol, Swarthmore, Pa.
- 2 Mev—Bonner, Rice Institute
- 3 Mev—Stephens, Pennsylvania
- 3 Mev—Tuve, Carnegie Institution
- 4 Mev—Herb, Wisconsin
- 4 Mev—Cooper, Ohio State
- 4 Mev—Lawrence, Berkeley
- 4 Mev—Schoup, Westinghouse
- 4.5 Mev—Waldman, Notre Dame
- 5 Mev—Fowler, Cal. Tech.
- 5 Mev—Van de Graaff, MIT
- 6 Mev—Turner, U. of Iowa
- 6 Mev—Johns Hopkins
- 6 Mev—Tate, Minnesota

Proposed or Under Construction

Cyclotrons
- 60 in.—Livingston, Brookhaven
- 60 in.—Van Atta, Southern California
- 60 in.—Oliphant, Birmingham, Eng.
- 60 in.—Loughridge, U. of Washington
- 65 in.—Medical Research Council, London, Eng.
- 74 in.—Bakker, Amsterdam, Netherlands
- 88 in.—Sieghahn, Sweden
- 92 in.—Svedberg, Uppsala, Sweden
- 92 in.—Bainbridge, Harvard

110 in.—Skinner, AERE, Harwell, Eng.
112 in.—Cruetz, Carnegie Tech.
130 in.—Barnes, Rochester
140 in.—Allison, Chicago
140 in.—Chadwick, Liverpool, Eng.
10 Bev synchro-cyclotron—Livingston, Brookhaven
165 in.—Dunning, Columbia

Synchrotrons
30 Mev—Fry, TRE, Malvern, Eng.
70 Mev—Fowler, Cal. Tech.
70 Mev—Swann, Bartol
70 Mev—Iowa State
100 Mev—General Electric
140 Mev—Collie, Oxford, Eng.
300 Mev—Wilson, Cornell
300 Mev—Crane, Michigan
300 Mev—Dee, Glasgow, Scotland
300 Mev—McMillan, California
300 Mev—Getting, MIT
300 Mev—Haxby, Purdue
300 Mev nonferrous—Lawson, G.E.
1300 Mev proton—Oliphant, Birmingham, Eng.

Betatrons
20 Mev—Tuck, Oxford, Eng.
30 Mev—Metro-Vic Co., Manchester, Eng.
30 Mev—Case School of Applied Science
70 Mev—Kerst, Illinois
100 Mev—Condon, Bureau of Standards
100 Mev—Allison, Chicago
300 Mev—Kerst, Illinois

Linear electron accelerators
—Swann, Bartol
—Hansen, Stanford
—Schultz, Yale
—Riecke, Purdue
—Fertel, Bristol, Eng.
—Fry, TRE, Malvern, Eng.
—Lawton, General Electric
—Westinghouse

Linear proton accelerators
—Alvarez, California
—Slater, MIT

Phillips generator
1 Mev—Dee, Glasgow, Scotland

Electrostatic accelerators
3 Mev—Thomson, U. of London
3.5 Mev—Brookhaven
3.5 Mev—General Electric
4 Mev—Schmidt, U. of Washington
5 Mev—Devons, Cambridge, Eng.
5 Mev—Fortescue, Harwell, Eng.
5 Mev—Argonne
5 Mev—Nielsen, Duke
12 Mev—Trump, MIT

OTHER NUCLEAR INSTRUMENTATION

High Resolution Mass Spectrometers*

Mass spectrometer
Crossed-field—Hipple, Westinghouse, Bureau of Standards
Large 60 deg—Beams, Virginia
Double focusing—Nier, Minnesota

Beta and Gamma Spectrometers

Spectrometers
Shaped-field beta—Cork, Michigan
Shaped-field beta—Mitchell, Indiana
Shaped-field beta—Hughes, Washington U.*
Shaped-field beta—Richardson, Edinburgh, Scotland*
Magnetic lens beta—TRE, Malvern, Eng.*
Magnetic lens beta—Klemperer, U. of London, Eng.*
Lens-type beta—Pollard, Yale
Magnetic-lens beta—Evans, MIT
Thin-lens beta—Mitchell, Indiana
Thin-lens beta—Hughes, Washington U.*
Thin-lens beta—Van Atta, Southern California†
Beta—Allen, Pittsburgh
Beta—White, Princeton*
Electrostatic beta—Van Atta, Southern California†

Spectrographs
180 deg beta—Hughes, Washington U.
180 deg beta—Mitchell, Indiana
Gamma—Bonner, Rice
Gamma—Hughes, Washington U.
Beta—Allison, Chicago†
Compound beta—Siday, Edinburgh, Scotland†
Double beta—Feather, Edinbugh, Scotland*

Crystal measurements of gamma energies—DuMond, Cal. Tech.*

New Counter Types under Research

Crystal counter studies
—Crane, Michigan
—Stephens, Pennsylvania
—Collins, Rochester
—Hofstadter, Princeton
—Street, Harvard
—Corson, Cornell
—Ahearn, Bell Laboratories
—Curtiss, Bureau of Standards
—Seitz, Carnegie Tech.†

* Under construction.
† Proposed.

Cerenkov counters
—Dicke, Princeton
—Rossi, MIT
—Street, Harvard

Scintillation photomultiplier counters
—Sherr, Princeton
—Collins, Rochester
—Getting, MIT

Electron multiplier development
—Sherwin, Illinois
—Van Atta, Southern California†
—Nier, Minnesota
—Stephens, Pennsylvania
—TRE, Malvern, Eng.

Microwave electron multiplier
—Miller, Pennsylvania

Other Counter and Circuit Research

Low voltage counters
—Friedman, Naval Research Lab.

Counters with organic gases
—Evans, MIT

Argon-butane counters—Swann, Bartol

Statistical fluctuations in counters
—Swann, Bartol
—TRE, Malvern, Eng.

Photosensitive counters—Swann, Bartol

Alpha counter design
—Feather, Edinburg, Scotland

Counter delay time
—Sard, Washington U.
—Sherwin, Illinois

BF_3 counter technique
—Wilson, Cornell

Gamma proportional counter
—Pollard, Yale

Helium proportional counter
—Bonner, Rice Institute

Thin window beta counters
—Swann, Bartol

Beaded anode counters
—Korff, NYU
—Curran, Glasgow, Scotland

Ten-cell Geiger counter
—DuMond, Cal. Tech.

General counter development
—Dunning, Columbia

High speed coincidence circuit methods
—Alvarez, California

Ultrafast coincidence circuits
—White, Princeton
—Schein, Chicago
—Schultz, Yale

Radioactivity instrument specifications
—Rose Committee, Argonne†

Special Cloud Chambers

High-pressure cloud chamber
—Johnson, Brookhaven
—Minnesota†

Balbon cloud chamber
—Johnson, Brookhaven
—Hazen
—Minnesota†
—Schein, Chicago*
—Anderson, Cal. Tech.*

Rocket cloud chambers
—Krause, Naval Research Lab.†
—Van Allen, Johns Hopkins†

36 in. cloud chamber in B-29 plane
—Anderson, Cal. Tech.

Triple cloud chamber and magnet tower
—Wilson, Manchester, Eng.

Large magnet cloud chamber in B-29 plane
—Anderson, Cal. Tech.
—Henderson, U. of Washington*

Combination cloud chamber and ionization chamber—Wheeler, Princeton†

Miscellaneous

Cyclotron magnet and coil design research—Creutz, Carnegie Tech.

Large magnetic analyzer for cyclotron beam—Kruger, Illinois

Large magnetic analyzer for synchrotron beam—Lawson, General Electric

Cosmic ray magnetic lens
—Schein, Chicago

Chronotron for short time measurements
—Neddermeyer, U. of Washington*

100 Atmosphere ionization chamber
—Dauvillier, Meudon, France

Velocity gage for high speed ions
—Kruger, Illinois
—Schoup, Westinghouse

Alpha ranges in photographic emulsions
—Hughes, Washington U., St. Louis

Photographic detection of nuclear particles—Pollard, Yale

Photographic plate meson work
—Powell, Bristol, Eng.
—Blackett, Manchester, Eng.
—Perkins, U. of London, Eng.
—Anderson, Cal. Tech†
—Salant, Brookhaven

COSMIC RAY RESEARCH

Meson Production and Absorption

Meson production at high altitude
—Schein, Chicago

Multiple meson production in paraffine
—Schein, Chicago

Meson production in paraffine in V-2 rocket
—Krause, Naval Research Laboratory

Meson production—Greisen, Cornell

Absorption of negative mesons
—Wheeler, Princeton

Meson absorption measurements —Street, Harvard†
Absorption of negative mesons—MIT

Meson Mass

Meson mass on ground and in B-29 plane —Brode, California
Meson mass in B-29 plane —Anderson, Cal. Tech.
Meson mass—Street, Harvard
Meson mass—Lowen, NYU†
Search for heavy meson by range-momentum data—Leprince, Ringuet, Ecole Polytechnique, Paris, France
Meson mass by triple cloud chamber tower—Wilson, Manchester, Eng.

Meson Disintegration and Lifetime

Lifetimes of positive and negative mesons—Schein, Chicago†
Meson lifetime at 11,000 ft—Schein, Chicago
Search for gamma ray from meson disintegration—Sard, Washington U. at St. Louis
Meson lifetime in absorbers—Sard, Washington U. at St. Louis
Meson lifetime in carbon—Lowen, NYU
Meson lifetime—Rossi, MIT
Search for neutron from meson disintegration—Sard, Washington U.

Showers and Stars

Structure of air showers—Rossi, MIT
Meson showers—Brode, California
Showers at high altitudes—Swann, Bartol
Giant showers at high altitudes—Schein, Chicago
Penetrating showers in planes—Braddick, Manchester, Eng.
Large air showers in airplanes—Auger, Ecole Normale Superieure, Paris
Large air shower counter array—Janossy, Manchester, Eng.
Shower studies over km spread—Auger, Ecole Normale Superieure, Paris
Air shower experiment—Rogozinski, Meudon, France
Mesons in showers—Montgomery, Yale
Penetrating showers with cloud chamber—Rochester, Manchester, Eng.
Shower detection by radar parabola—Lowell, Manchester, Eng.
Shower measurements in V-2 rocket—Krause, Naval Research Laboratory
Rocket studies of showers—Van Allen, Johns Hopkins
Star production at 14,000 ft—Wheeler, Princeton
Star studies with ionization chamber—Montgomery, Yale
Star production—Greisen, Cornell
Nuclear stars at high altitudes—Brode, California

Miscellaneous

Slow meson energy spectrum, high altitudes—Schein, Chicago
Meson intensity at high altitudes—Swann, Bartol
Slow meson intensity, high altitudes—Rossi, MIT
Slow meson reactions in cloud chambers —Wheeler, Princeton
Meson spectrum—Rogozinski, Meudon, France
High altitude meson intensity—Dymong, Edinburgh, Scotland
Magnet cloud chamber work at 11,000 ft—Mageotte, Ecole Polytechnique, Paris, France
Azimuth and altitude variation of the penetrating rays—Swann, Bartol
Latitude variation of meson intensity—Swann, Bartol
Soft component in balloons—Schein, Chicago
Maximum of the soft component in V-2 rocket—Krouse, Naval Research Laboratory
Fast electrons at high altitude—Rossi, MIT
High altitude electrons in V-2 rocket—Krause, Naval Research Laboratory
Neutron intensity in V-2 rocket—Van Allen, Johns Hopkins†
Neutron production in balloons—Korff, NYU
Cosmic ray neutron intensity—Montgomery, Yale
Neutron intensity at various altitudes—Wheeler, Princeton
High altitude neutron intensity—Simpson, Chicago†
East-west asymmetry of high altitude penetrating component—Schein, Chicago†
East-west asymmetry in V-2 rocket—Van Allen, Johns Hopkins
Search for negative proton in V-2 rocket —Krause, Naval Research Lab.
Primary energy distribution from balloon flights—Neher, Cal. Tech.
Sign of incoming primaries—Neher, Cal. Tech.
Directional distribution of primaries—Wheeler, Princeton†

* Under construction.
† Proposed.

Balloon measurements of primaries—Rossi, MIT
East-west effect at high altitude—Brode, California
Proton intensity in balloons—Korff, NYU
Fluctuations in cosmic ray intensity
—Broxon, Colorado
—Forbush, Carnegie Institution
—Duperier, U. London, Eng.
—Dolbear, Manchester, Eng.

THEORETICAL STUDIES

Theory of angular distribution in disintegrations—Breit, Yale
Slow neutron scattering theory—Breit, Yale
Theory of angular distribution in meson production—Kusaka, Princeton
Theory of proton-proton scattering—Peierls, Birmingham, Eng.
Range and energy curves for cosmic ray particles—Wheeler, Princeton
Theory of meson absorption—Weisskopf, MIT
Cosmic ray primary interaction with photons—Primakoff, Washington U. at St. Louis
Theory of penetrating showers—Janossy, Manchestor, Eng.
Relativistic corrections to nuclear moments—Breit, Yale
Theory of nuclear moments—Primakoff, Washington U. at St. Louis
Deuteron theory—Weisskopf, MIT
Theory of the nuclear energy surface—Primakoff, Washington U., St. Louis
Statistical nuclear theory—Weisskopf, MIT
Alpha particle theory of heavy nuclei—Breit, Yale
Theory of neutron diffusion—Wick, Notre Dame

NUCLEAR SPECTRA AND ENERGY LEVELS

H^3 beta endpoint—White, Princeton
C^{14} half-life—Evans, MIT
C^{14} and Be^{10} spectra in cloud chambers—Stephens, Pennsylvania
K^{40} spectrum—Van Atta, Southern California†
Sc^{46} spectrum—Mitchell, Indiana
Ti^{51} spectrum—Swann, Bartol†
Ma^{55} energy levels—Pollard, Yale
Ga^{72} spectrum—Swann, Bartol
Ge^{72} energy levels
—Goldhaber, Illinois
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In^{116} spectrum—Swann, Bartol
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Ca^{137} spectrum—Allen, Pittsburgh
Ta^{182} spectra—Cork, Michigan
Ir^{191} resonance neutron capture—Goldhaber, Illinois
Ir^{194} spectrum—Cork, Michigan
A^{198} spectrum
—Cork, Michigan
—Mitchell, Indiana
Indium periods—Bradt, Purdue
Gamma resonance widths in beryllium—Lauritsen, Cal. Tech.
Tungsten beta spectra—Mitchell, Indiana
Search for Ionium and Po gamma rays—Feather, Edinburgh, Scotland
Possible radioactivity of Nd—Feather, Edinburg, Scotland
Proton groups from sulphur—Pollard, Yale
Proton resonance widths in Li, Be, C—Lauritsen, Cal. Tech.
Short-lived metastable states—Goldhaber, Illinois
Short-lived isotopes
—Allison, Chicago
—Van de Graaff, MIT
—Turner, Iowa†
—Lauritsen, Cal. Tech.
—Waldman, Notre Dame†
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Lifetimes of excited states—Feather, Edinburgh, Scotland
Low energy endpoint of beta spectra—Butt, Edinburgh, Scotland
Beta spectrum shape—Turner, Iowa†
Analysis of complex beta spectra—Van Atta, Southern California
Neutron resonances around ½ Mev—Falk, Carnegie Tech †
Gamma spectra from thermal neutron capture—Goldhaber, Illinois
Gamma ray spectra—Shire, Cambridge, England
Radioactivity tables—Sullivan Committee, Harvard†
Energy level survey article—Pollard, Yale†
Energy level summary—Deutsch Committee, MIT†

SCATTERING AND ANGULAR DISTRIBUTION

12 Mev neutron-deuteron scattering—Kruger, Illinois
12 Mev neutron-proton scattering—Kruger, Illinois
Proton-neutron scattering—Hughes Washington U. at St. Louis

Fast neutron scattering—Tate, Minnesota
Fast neutron scattering in gases—Bonner, Rice
30 Mev neutron scattering—Allen, Pittsburgh†
Proton-proton scattering
—Kruger, Illinois
—Hughes, Washington U., St. Louis
Deuteron-proton scattering—Kruger, Illinois
Deuteron scattering by light nuclei—Evans, MIT
Resonant gamma scattering—Pollard, Yale
Nuclear scattering of gamma rays—Weisskopf, MIT
Electron-positron scattering—White, Princeton
Angular distribution of photoneutrons—Hughes, Washington U., St. Louis
Angular distribution of neon alphas—Lauritsen, Cal. Tech.
Angular distribution of disintegration products—Turner, Iowa†

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Fast neutron absorption—Allison, Chicago
Gamma absorption measurements—Pollard, Yale
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—Kruger, Illinois
—Van de Graaff, MIT
—Collie, Oxford, Eng.
Alpha-proton reactions—Mitchell, Indiana
Deuteron disintegration of Beryllium—Bonner, Rice institute
Deuteron disintegration of Nitrogen—Tate, Minnesota
Proton disintegration of Fluorine—Bonner, Rice Institute
Proton disintegration of Carbon—Lauritsen, Cal. Tech.†
Proton disintegration of Nitrogen—Lauritsen, Cal. Tech.†
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—Lauritsen, Cal. Tech.
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Stars from 100 Mev neutrons—Powell, California

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Neutrino experiment with He^6
—Allison, Chicago
—Booth, Columbia
Neutrino detection by Li disintegration
—Lauritsen, Cal. Tech.
—Bonner, Rice
Neutrino recoil studies—Sherwin, Illinois
Neutrino recoil detected by Ne discharge—Hughes, Washington U. at St. Louis
Neutrino mass from H^3 spectrum—White, Princeton
Value of maximum possible neutron charge—White, Princeton

NUCLEAR MOMENTS

Nuclear moments, microwave method
—Purcell, Harvard
—Dunnington, Rutgers
—Rollin, Oxford, Eng.
Nuclear moments, atomic beam method—Rabi, Columbia
Nuclear moments, magnetic induction method—Bloch, Stanford
C^{14} spin—Stephens, Penn.
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† Proposed.

RADIOACTIVE TRACERS IN FRICTION STUDIES

Detailed analysis of new results, experimental techniques, and principles of friction studies with radioactive isotopes. Applications to study of lubricants, metal wear, and other well-known but unexplained phenomena are suggested

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WHILE THE PHENOMENON of friction has been familiar to man for many centuries and he makes good practical use of it in a variety of ways, his knowledge of what causes it is very incomplete. It first attracted the attention of Leonardo da Vinci but serious study of the phenomenon begins with Amontons (*1*) and Coulomb (*2*). They enunciated the simple empirical laws of friction taught in most schools. On the basis of their observations, Coulomb made the hypothesis that friction is due to the geometrical interference of the many small roughnesses on the two rubbing surfaces. In particular, the force of friction is the force necessary to slide the protuberances on one surface up the slopes of those on the other surface against the action of the normal force holding the two together. A simple resolution of the forces involved shows that the friction force should be linearly proportional to the normal force, in accord with observation. The constant of proportionality is the tangent of the average slope of the surfaces.

This roughness hypothesis had many defects, however. Most notable is the fact that as the surfaces were made smoother the friction coefficient did not progressively decrease as it should, but leveled off at a finite value. Also the advent of surface roughness measuring instruments demonstrated that surfaces of different materials having the same roughness may have markedly different friction coefficients. These facts indicate that other mechanisms are at work.

Load Carried by High Points

Tomlinson (*3*), Derjaguin (*4*), Hardy (*5*) and Bowden (*6*) have postulated that an important component of friction is that due to the molecular adhesion between the two surfaces in the regions where there is intimate contact. In more detail their picture is as follows. When two solid surfaces are pressed into contact, the total load is carried by the few highest points which are in intimate contact. These taken together constitute a very small area and only a small fraction of the nominal area of contact. Hence on these areas the local pressures are very high, generally exceeding the yield point of one or both of the materials in question. Because of these high pressures, it is argued, a species of welding is formed even at temperatures far below the normal melting point. If in addition there is relative motion of the two surfaces or rubbing, the heat produced will further

increase the tendency to weld. The force of friction is the summation of the forces necessary to break all of these minute local welds when sliding takes place. This would explain among other things the almost universal observation that the static friction force is greater than the kinetic.

If there is little affinity between the materials of the two surfaces, the break in the weld will usually occur along the original juncture. If, on the other hand, the two materials are the same or similar, then the weld will be relatively large in extent and it will be strengthened through the work-hardening of the rubbing. If it is harder and stronger than either of the constituent metals, the shearing due to the driving force may be expected to take place within the bulk of the weaker metal.

As a result, after the weld is broken, a small blob of the softer metal should be found adhering to the harder. This can actually be observed in extreme cases as when a pencil of lead is rubbed severely over steel. It may also be observed between harder metals if the rubbing speed is high. The high speed produces extreme working and hardening of the smallest momentary weld. The high temperature produced by the friction at these speeds causes sufficient softening of even relatively hard metals for them to shear, leaving large areas of one metal adhering to the other. This is known as galling and is a common cause of failure in high-speed machinery if the lubrication fails suddenly.

In the severe cases, the transferred metal can be easily observed, but in the more usual case of friction under moderate loads and speeds the only observable effects are smoother or slightly scratched areas on the rubbing parts. In even milder cases, there are no visible effects to the naked eye, and the optical microscope shows little more. Hence the detection of transferred material becomes a critical problem. It is also an important problem as being prima facie evidence for the existence of the adhesion component in friction which we have been discussing. At this point it should be noted that there are other possible components in friction which may be important or even predominate under certain circumstances. These include, in addition to the mechanical interlocking of roughnesses already mentioned, the plowing or gouging of a softer material by a harder (*6*) and possibly electrostatic effects in the case of dielectrics (*7*). On the plowing hypothesis, metal might be expected to be picked up or transferred but there must also be some type of adhesion holding the particle to the ploughing surface.

Friction Research Methods

The methods that have been or might be used to detect the transferred material will be considered next. As mentioned before, the optical microscope yields little evidence; microchemical analysis is no better. The quantities to be dealt with are too small and are difficult to isolate in a sample. The first method that yielded any positive evidence was the taper-sectioning method described by Nelson (*8*) and applied by Bowden, Moore and Tabor (*6*) to this problem. The method consists of sectioning the friction sample at right angles to the direction of rubbing and at a very small angle with the surface. The section when metallographically polished and examined under the microscope shows the profile of the surface with an artificially exaggerated vertical magnification as compared to the horizontal one, often as much as 10 to 1. Thus the surface roughness is exaggerated and the smallest protuberance is magnified. In addition the small inclination of the section to the surface increases the

probability of intersecting any foreign material on the surface.

Bowden, Moore and Tabor tapersectioned a steel surface on which a copper rider had been rubbed. Fig. 1, reproduced from their paper, is the profile of the steel surface so obtained showing the scratching and working of the steel under the friction track and also a small blob of copper adhering to the steel surface. This method, however, has the disadvantages that it is laborious, it destroys the sample and it gives little idea as to whether this pick-up is a usual concomitant of friction or a rather infrequent and fortuitous occurrence. It can give little quantitative measure of the amount transferred and it would have difficulty in distinguishing like materials, as steel on steel. On the other hand, it does show the dimensions and shape of the adhering particle.

The second method of detecting transferred material is an electrographic one applied by Hunter, Churchill and Mears (*9*). It consists of applying a gelatine-coated paper which has been soaked in a suitable electrolyte to the friction surface and passing a small current through it so that the metallic ions pass into the gelatine. The metal ions concentrate in the gelatine in a pattern corresponding to their distribution on the solid surface, and their pattern can be rendered visible by a proper spot reagent. These workers applied it to copper sliding over lubricated platinum with good results. This method can give a qualitative estimate of the amount transferred but its resolving power is poor, i.e. it cannot show details of the friction track, and it is limited to dissimilar metals.

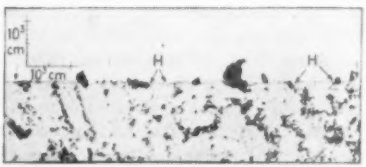

FIG. 1. Taper section of track formed by sliding a hemispherical copper rider on an unlubricated steel surface. Horizontal magnification 200. Vertical magnification 2000. The width of the track is indicated by arrows. Note the adhering fragments of copper and pits marked "H" where the steel has been plucked out of the surface(*6*).

A third possible method is one recently described by J. J. Trillat (*10*). In it, one exposes the rubbing surface against which is pressed a photographic film to a vertical beam of high-energy X-rays (250 kv). These X-rays traverse the film with little photographic effect due to their high energy but, on striking the rubbing surface, particularly if it is a metal, energetic secondary electrons are emitted, their number and energy being characteristic of the metal irradiated. These electrons blacken the photographic film, the density varying with the electron density and hence with the metal emitting them. Thus it should be possible to detect the track of a metal smeared on another metal. The resolving power should be limited only by the grain size of the photographic emulsion. This method is also limited to dissimilar materials. It has not yet been applied to this friction problem so far as the author is aware but it has much to recommend it and should be explored.

Radioactive Tracer Method

The fourth method which can be employed for detecting the material transferred on rubbing consists of making one of the two rubbing materials radioactive, rubbing them together and then examining the second surface for activity. It should have great sensitivity, would not be limited to dissimilar materials and should be capable of being put on a quantitative basis.

In the initial experiments using this method (*11*), a beryllium-copper block was bombarded with a beam of deuterons from a cyclotron producing

active copper and zinc by the nuclear reactions:

$$Cu^{63} + d \rightarrow Zn^{63} + 2n$$
$$Cu^{63} + d \rightarrow Cu^{64} + p$$

These decay with half-lives of 38 minutes and 12.8 hours emitting beta and gamma rays in the process. The friction experiments consisted of rubbing small spheres of various materials, including a variety of metals and one glass, over the surface of the beryllium-copper block under various loads and for various distances. In general, the conditions of rubbing were mild. Both the hardness and the surface roughness of the spheres were varied. Most of the rubbing was done dry although in a few cases a purified white mineral oil was used.

The spheres were then exposed to a Geiger-Müller counter. In all cases, some activity was noted. It is known that the radiations themselves from these isotopes cannot induce any appreciable activity in the materials examined. Furthermore, fairly vigorous rubbing of the spheres with a Kleenex towel failed to remove the activity from the spheres although some small amount was picked up by the towel. Thus the mechanism of material transfer during rubbing was confirmed both for a variety of combinations of materials and for mild rubbing conditions.

Some quantitative measurements of dependence on rubbing conditions and material properties were made but these measurements had very poor reproducibility for reasons which will be discussed.

Activating the Friction Specimen

There appear to be four general methods for rendering one of the two rubbing members radioactive. Two of these methods concentrate the activity on or near the surface, and two spread it uniformly throughout the volume. Each has certain advantages and disadvantages.

The first of the surface methods, and in fact the first that was actually tried, (*11*), consists of preparing the friction specimen in its desired form as regards constitution, shape and type of surface, and then exposing the rubbing surface to irradiation by a beam of charged particles, usually deutrons or protons. The accelerating apparatus for these particles may be an electrostatic generator or a cyclotron. The penetration of the particles into the solid material is so small (of the order of microns) that all of the radioactive atoms produced by the bombardment are concentrated in the surface layers.

This is advantageous in keeping the total activity of the specimen low so that it may be safely handled. On the other hand, it was found that owing to the sharp gradient in activity with depth it was very difficult to obtain an accurate sample of the material transferred to use as a basis for determining the specific activity. Furthermore, not only did the specific activity vary with depth, but it also varied across the face of the sample owing to variation in intensity over the cross section of the bombarding beam. This can be obviated to some extent by oscillating or rotating the specimen during the exposure. Also the local heating of the surface due to bombardment will oxidize it even in the reduced pressure of a cyclotron, thus changing its friction characteristics. This requires either internal cooling or a subsequent refinishing of the surface.

An alternative method of concentrating the activity entirely on the surface is to prepare the friction specimen in desired form and then to electroplate on it a thin layer of the active material. The two should be of the same chemical species so that a subsequent heating above the recrystallization temperature will cause the plate to become an integral part of the substrate and possess frictional properties charac-

teristic of the bulk material. This heating will also require a final finishing operation on the surface to remove the scale and give the desired surface roughness.

This method has the advantages over the first method of permitting an accurate sampling of the specific activity of the surface, usually by taking a sample from the plating bath, and of being easier to do in small or remote laboratories since the common radioactive isotopes can be purchased quite reasonably through the Atomic Energy Commission. It has the drawbacks of possible weakness in the bond between the plate and the base and uncertainty of reproducing the frictional characteristics of bulk metals in which one is principally interested.

If the disadvantages of both of these methods are really objectionable, then one can resort to volume methods of activation. These are generally free from the above objections but they spread the activity throughout the whole specimen. This renders it difficult to handle from a safety point of view. One of these methods consists of adding a radioactive isotope to a melt of the metal in which one is interested and then fabricating the friction specimen from this heat (*12*). This requires carrying out a complete series of foundry, heat-treating and machining operations which is quite laborious and time-consuming. The size of the specimen must be kept inconveniently small for reasons of safety during the fabricating steps and because of the expense of the active isotope. On the other hand it permits wide latitude in the choice of isotope.

A fourth method consists of first preparing the specimen in its final form and then exposing it to an atmosphere of slow neutrons such as exists in the uranium chain-reacting pile of the Clinton National Laboratory at Oak Ridge. This gives a uniform specific activity throughout the sample and does not require any subsequent finishing of the surface. The choice of isotopes, however, is limited to those that can be produced by slow neutrons, and the upper limit of specific activity is governed by the capture cross section for slow neutrons. These limitations are not serious for most types of friction experiments. Also, other undesired radioactive isotopes may be produced which are troublesome from a handling and shipping viewpoint but are too short-lived to be useful as friction tracers. The over-all dimensions of the specimen are limited, at present at least, by the dimensions of the aluminum irradiation containers used at Oak Ridge which are cylinders ¾ in. in diameter and 3 in. long. The Isotopes Division of the AEC has been very cooperative and helpful in undertaking the irradiation of solid specimens and the charges for these irradiations are quite reasonable.

Three of these four methods have already been employed in the author's laboratory and the plating method is now under consideration for some related experiments.

Choice of Materials

All solid materials, metal and nonmetal, are of interest from the standpoint of friction. Hence one approach to the problem would be to choose the material whose radioactive properties are most suitable for the experimental method and use it exclusively on the assumption that its frictional properties will be typical. This dictated the choice of copper in the initial experiments. However, it turns out that with the variety of possible irradiations and detecting instruments now available most of the metals and a number of non-metals are usable although some may require more ingenuity in their use than others. For this reason the selection of materials may just as well

be dictated by practical and engineering interest as regards their frictional behavior.

There are several categories of friction materials in decreasing order of interest, namely, steels, bronzes and copper alloys, white metals, and nonmetals. It may seem strange that the white metals, comprising lead, tin, cadmium and indium, should fall so far down the list since their alloys, the tin and lead babbitts, are among the most important bearing materials. However, the babbitts are always used in bearings where a hydrodynamic oil film is expected to develop, thus completely separating the rubbing surfaces, so that metal-to-metal contact should occur only infrequently. When it does, the primary requirement is that as little heat be produced as possible. This dictates the use of a metal with a low shear strength. To a lesser degree, the same argument holds for the bronzes and copper alloys which may sometimes contain segregated lead. On the other hand steels are used where little or no lubrication is to be expected; hence their solid friction properties are of primary importance. Even when babbitt or bronze bearings are used the rotating shaft is generally made of steel. Thus, the use of radioactive iron and the common alloying elements in steel will be considered first.

In a systematic consideration of all the possible radioactive isotopes which might be used as tracers in connection with the transfer of a particular metal or alloy, the method of irradiation must be known. For instance, if the fully fabricated friction specimen is to be bombarded by deuterons, protons or neutrons, then the possible isotopes of interest are those produced *from* the chemical species of the metal or alloying elements of which it is composed. If, on the other hand, one proposes to add an active isotope by mixing in the molten state or by plating, then the chemical species of the active isotope should generally be either that of the metal in question or readily soluble therein.

Radioisotope Properties

As regards the radioisotope itself, there are three properties which it is desirable, although not necessary, that it possess. First, its disintegration radiation should be of high energy so that the effect of geometry on the counting rate is not so critical. Secondly, it should have a reasonably long half-life particularly if it is to be shipped some distance after activation or if it is to be added to a melt which is to be followed by time-consuming metallurgical operations. Thirdly, its concentration in the whole alloy or specific activity should be high if the method is to be sensitive enough to detect the transfer of a fraction of a microgram of material.

For instance, in the case of the mild steels the common alloying or impurity elements in addition to iron itself are carbon, manganese, silicon, phosphorus and sulphur, none of which are present to the extent of more than one per cent. Irradiation of these elements in the friction specimen itself does not give a high enough specific activity for the most sensitive measurements. Iron has two isotopes, Fe^{59} and Fe^{55}, produced by irradiation with deuterons or slow neutrons, which decay with the emission of soft beta rays and X-rays respectively. Their specific activity in pure iron at saturation is not particularly high. When bombarded with deuterons iron also yields active isotopes of cobalt and manganese but only in moderate concentration. Thus none of the constituents of the plain carbon steels is very satisfactory in providing active isotopes when irradiated in the friction specimen.

If it is possible to add a radioisotope to the melt from which the friction

specimen will be made, the situation is much better. S^{35} which can be obtained in separated form, i.e., undiluted with inert "carrier," can be added to the melt up to the limit of the nominal composition and produce a sufficiently high specific activity. Mn^{52} and P^{32} can also be used although their half-lives are somewhat short, 6.5 days and 14.3 days, respectively. When one contemplates a complete series of steel-making steps to fabricate the friction specimen. C^{14}, even in separated form, does not have a sufficiently high specific activity.

Coming to the alloy steels there are additional elements available. The most common alloying element is chromium which also fortunately provides useful tracer isotopes. It will yield Cr^{51} on irradiation by neutrons and Mn^{52} on bombardment by deuterons both of which are useful, or Cr^{51} may be added to the melt. In the absence of chromium a less satisfactory substitute is molybdenum, Mo^{99}.

Among the nonferrous friction metals, copper, tin and lead form the principal constituents of the bronzes and the babbitts. Cu^{64} can be produced in quite high concentration either by bombardment of copper with deuterons or by irradiation with slow neutrons and is a very sensitive indicator, probably the best of the useful friction metals. Bombardment of tin with deuterons can produce Sb^{124} with a half-life of 60 days, but its specific activity is not nearly so high as the copper. The best source of radioactive lead is the decay product of the radium series, Pb^{210} (RaD), and its daughter, Bi^{210} (RaE), with which it is in equilibrium. This can be procured quite easily from the radium companies and plated on the bearing surface.

Friction Experiments

At this point, it is in order to mention some of the salient features of well-controlled friction experiments as these will determine to some extent the best methods for measurement of the activity. The simplest and most obvious quantity to measure when two solid bodies rub together is the friction force. As already mentioned, Amontons (*1*) and then Coulomb (*2*) early made a thorough study of this quantity. The next most important quantity to measure would be the area of contact over which the friction force is exerted. It was observed early that this was not the area of the nominal plane of contact since the friction force was largely independent of this area of contact.

High and Low Areas Always Present

No solid surface can be considered even remotely flat on an atomic scale; it has high areas and low areas like a rather hilly terrain. When two solid surfaces are brought into contact it is evident that only in three or a few more isolated regions are the atoms of the two surfaces in intimate enough contact for their repulsive forces to come into play and support the load. The remainder of the two surfaces are still separated by thousands of Angstroms or atom diameters. By a very plausible argument, Bowden and Tabor (*14*) have shown that the sum of these small isolated areas which actually carry the load is approximately equal to the load forcing the two surfaces together, divided by the pressure necessary for plastic flow of the softer surface.

Obviously, as the load is applied, the higher points on the surfaces flow plastically. This enlarges their areas and brings others into play until the relation above holds, after which plastic flow ceases. Calculations from this relation show that in most cases the true area of contact is only a very small fraction of the nominally observed one. These were confirmed by measurements of the electrical conductance between solids in contact (*14*).

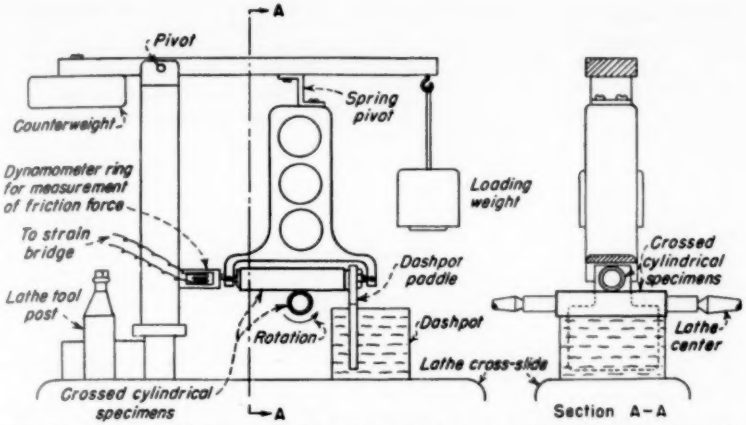

FIG. 2. Sketch of friction apparatus which makes use of lathe spindle to rotate the moving specimen. The friction force is measured by means of strain gages.

From the above, it is evident that in such situations as a rectangular block resting on a plane the true contact area will be difficult to locate, much less measure, with certainty and that it will probably shift position during sliding due to wear. The better geometrical arrangement is to use convex rather than plane surfaces in the region of contact, such as a sphere on a plane, a sphere on a cylinder or two crossed cylinders thus achieving what Bowden calls a "concentrated area of contact." The contact area can be located with greater exactness and the wear track or spot when observed can be checked against the Hertz equation for elastic deformation in the lower range of loads.

Continuous motion with the above shapes can be obtained with a small sphere riding on a rotating flat disc, with a fixed cylinder riding at right angles on a rotating one or with a sphere riding in the depression formed by three fixed ones. A sketch of a simple arrangement employing the second of these arrangements is shown in Fig. 2. The jig holding the stationary or riding cylinder can be mounted in the tool post of a simple bench lathe and make use of the lathe spindle to rotate the moving cylinder. Load and speed can be varied and friction force measured by strain gages.

Another characteristic of friction experiments is their extreme sensitivity to the state of cleanliness of the rubbing surfaces. While it is easy to perform experiments dry, that is, without purposely using a lubricant, it is extremely difficult to perform experiments on clean, bare surfaces. In fact, clean bare metal surfaces only approach achievement in a high vacuum after out-gassing. In such cases, friction coefficients as high as 6 have been observed (*15*). No matter how carefully these same surfaces are cleaned in air, the coefficient is never greater than unity.

Absorbed layers of oxygen and water vapor, oxides and grease from the city air all act as adventitious lubricants, their effect being universally to reduce the friction. This is fortunate for us in everyday life or things would be

much stickier than they actually are. It is characteristic of most "dry" friction experiments that the friction is lower at the beginning of a run and increases as traces of lubricant are worn away. The steady value to which it rises is determined not only by the materials in contact, but also by how frequently the contact areas are wiped clean of oxide and gas films. This frequency determines how effectively these films can repair themselves between cycles to keep the friction low.

Hence cleanliness of the rubbing surfaces is all important. Abrasion is by far the best way of attaining it. When performed with or under a degreasing agent such as benzene it is very effective. A simple test for the absence of greases is the even spreading of a drop of water on the surface with a zero advancing contact angle in all directions. These cleaning considerations must be taken into account in deciding on the method and degree of activation of a specimen since the above operations are difficult to carry out effectively at a distance of two feet or more.

In using an apparatus of this type for transfer experiments, the activated specimen may be either the stationary or the rotating one. In the former case, the transferred material will be spread out along a friction track on the rotating one while in the latter the transferred active material will be concentrated in the vicinity of a single wear spot on the stationary specimen. Every transfer experiment to be complete should run the active specimen in each of these positions in separate runs to measure the transfer both ways since the roles of the stationary and of the moving member of a rubbing pair are generally quite different.

Table 1, which is reproduced from the paper by Sakmann, Burwell and Irvine (*11*), tabulates the amount of material transferred from a moving beryllium-copper block to stationary riders of various materials, both cut from solid stock and electroplated on steel. It gives an idea of the order of magnitude of the weight of transferred material which we are trying to detect.

Table 1

Weight of Material Transferred from Beryllium-copper Block to Riders of Various Materials

Material	*Weight transferred (micrograms)*
A. Cut from solid stock	
Beryllium-copper	0.025
Aluminum	0.013
Phosphor bronze	0.091
Zinc	0.022
Cadmium	0.023
Tin	0.026
Lead	0.036
B. Electroplated	
Antimony	0.014
Nickel	0.0028
Silver	0.0073
Chromium	0.00012

Detection Methods

The means of quantitatively measuring the active material which may be left associated with a friction track or a wear spot on an inactive surface is the Geiger counter. Depending on the isotope in question, the counter is designed specifically to detect beta rays, gamma rays, or X-rays.

As the whole subject of Geiger counters is discussed in great detail in other articles in this journal, it will not be discussed further here except for the mention of one point about geometry. For most of the work done to date, the bell-type counter has been used largely because it is available. However, this often requires removal of the active material from friction specimen and plating on a flat planchet in order to attain greatest sensitivity. This is laborious and time-consuming so that

comparable sensitivity might be attained by designing a counter of special geometry for measuring the active material on the cylindrical specimen in situ.

In the study of a two-phase bearing alloy such as copper-lead or the lead bronzes, it is of interest to know whether either phase is transferred preferentially. This can be done most accurately by introducing a beta ray emitter into one phase and a gamma or X-ray emitter into the other one. Then following a method described by Peacock *et al.* (*16*), two counters are used, one filled with helium and having a thin mica window which counts electrons but which is very insensitive to gamma or X-radiation and the other filled with argon and having a beryllium window which keeps out electrons but is relatively effective in detecting X-rays. By the use of both these counters on a sample of the original activated bearing material and then on the friction track or wear spot, the ratio of their responses in the two cases will show whether there is preferential transfer of one phase over the other.

The quantitative information given by the Geiger counter can be supplemented by a photographic method described by Gregory (*17*). This consists simply of placing a photographic film in contact with the surface carrying the friction track and allowing the latter to take its own picture. Gregory used Super XX plates in his original work. The author has gotten good results using Eastman duplitized no-screen X-ray film with exposures of 24 to 48 hours if no magnification is required. If more resolution is desired, the various spectrographic films may be used with a corresponding increase in exposure time. The film must be in firm contact with the solid surface to obtain a sharp picture. This can be done by backing it up with sponge rubber. No special development procedure is required.

The photographic method has the advantage over the counter in being able to show the distribution of the material along the friction track. In the case of a single wear spot it will not be as helpful. The photograph of four such tracks around a cylindrical specimen is reproduced in Fig. 3. (The film was wrapped around the cylinder so that each of the straight paths in the picture depicts a circular track which closes on itself.) In this case the cylinder was a hardened alloy steel and the active rider was a cylinder of mild steel which had been irradiated in the Clinton pile at Oak Ridge. Gregory used radioactive lead on copper, steel and lead. The tracks reproduced in his paper show a broad solid smudgy type of track, sometimes with evidence of chatter, due in part to the mechanics of the system. Fig. 3, on the contrary, shows that for harder materials like the steels the metal is not smeared on in a solid track but rather is laid down in discrete spots or globules. It is interesting that the tracks of these two metals differ so in this respect. This may be due to their difference in hardness.

Preparation for Measurement

In the quantitative measurement of the amount of transferred active material by means of Geiger counters the geometry and state of this material may be important, particularly if its radiation is soft. The most straightforward method, of course, is to expose the friction specimen carrying the track directly to the counter in some jig to accurately and reproducibly locate it. The method is convenient for quick preliminary checks and for comparative work. However, it has two disadvantages. First, it does not give the maximum possible sensitivity with a counter having a flat end window (bell type) because not all of the friction track can be gotten equally close to the

FIG. 3. Radiograph of four friction tracks made by activated mild steel rubbing on alloy steel. Note that the transferred material has adhered in discrete spots, possibly corresponding to local "welds." No magnification.

counter window at one time and also because part of the track is shielded from the counter by the specimen itself. Secondly, if the activity is measured in situ, then additional calibrating steps are required to convert the counts per minute as measured into weight of active material.

For calibration and for greatest sensitivity it becomes necessary, in a certain percentage of the cases at least, to remove the material in the vicinity of the friction track which will include the active material if any has been transferred from the friction specimen. Mechanical methods of removal such as by machining have not been found satisfactory, presumably because of the difficulty of recovering all the material. It cannot be done on hardened steels and any abrading or grinding is out of the question. Chemical removal has been found to be the best. The friction specimen is completely coated with a stripping lacquer except in the vicinity of the friction track to be removed. This is to reduce the amount of inactive metal dissolved from the specimen as a whole which only dilutes the small amount of active metal to be detected. The active material is then removed in an acid solution. If it emits strong gamma radiation, this solution, after reduction by evaporation to a standard volume, can then be counted directly by the counter. The count can be calibrated by dissolving a known weight of the activated specimen in the same acid and taking the same volume of the solution. To minimize the effect of the absorption of the radiation in the liquid, the solution containing the known weight of metal should be so diluted that a standard volume of it gives approximately the same counting rate as the unknown. Then from the weight of dissolved metal, the degree of dilution and the ratio of the counting rates, the weight of active material in the unknown solution can be computed.

Often, however, as with the iron and chromium radioisotopes, their radiations are so strongly absorbed in the liquid that only a small proportion escapes and is counted. In this case, the metal must be deposited in a solid condition and all the liquid removed. This deposition may be simply the residue left from evaporation of the water from the solution, it may be electroplated, or it may be precipitated and removed by filtration. Simple evaporation has not been found satisfactory largely because the residue is not left spread in a uniform layer as the liquid evaporates. This produces large and variable absorption within the solid material.

For those metals and alloys that can be quantitatively plated, electroplating is the most satisfactory method. However, each metal generally requires the working out of a different quantitative plating procedure. This is a major research problem and there is surprisingly little data in the literature on the quantitative removal of metals from solution by electroplating. Peacock *et al.* (*16*) have worked out such a method for iron which is completely satisfac-

tory and is recommended for use. A standard quantity of iron, say 10 milligrams, containing the active iron is electroplated on a flat copper planchet in a circular area of uniform thickness ⅛ in. in diameter. In this way the absorption is constant and relatively small for each sample, and it can be placed quite close to the window of a bell type counter. Both the known and the unknown are plated in the same way so that the weight of active iron in the known plate and the ratio of the two counts give the weight of active iron in the unknown.

Chemical Precipitation

For those metals and alloy mixtures that cannot be plated quantitatively, chemical precipitation from solution seems to be the best possibility. It is less dependable and reproducible than the plating, largely because of the filtering step. The active precipitate should be left on a small piece of good quality filter paper in a circular area of uniform thickness. The variability of penetration of the precipitate into the pores of the filter paper thus producing variable absorption of the radiation may account for some of the scatter in results. The filtrate should be checked by a sensitive spot test for absence of the metal in question. Often the precipitate when dry is loose and powdery and should be held in place by some kind of binder such as a plastic in a very dilute water solution. With care the precipitation method can be made to yield useful results.

In all of the above, it has been implied that the transferred material is strongly adhered to the other surface. In actual fact, this is an oversimplification. Apparently the material is attached with all degrees of firmness. Some is so firmly bound that even after abrasion with emery paper to such an extent that the track is no longer visible to the eye, its vicinity will still show definite activity. Some is more loosely bound, so that vigorous rubbing with soft paper like Kleenex will rub it off, as evidenced by reduction in friction and darkening of the Kleenex which then shows activity. Still other material is visibly resting on the surface as dust and can be shaken off. Finally, of course, a certain fraction of the material worn off the first surface is never collected on the second surface at all but becomes completely severed from both surfaces as wear particles. These particles may linger in the vicinity to be caught later between the rubbing surfaces and produce further wear and galling, or they may be carried away either by gravity, by air currents, or by a fluid lubricant.

The study of these wear particles is a fertile field of investigation in itself and one that merits more attention. A great many empirical measurements have been made of the total wear in various test machines as measured by weight loss or dimensions of wear spot but little study has been made of the individual wear particle or the process by which it is removed. Making the parent material radioactive should make it easier to follow its progress through the system. Electron microscope pictures of the particle's profile may indicate how it was removed.

The presence of lubricant adds an additional factor to the rubbing system. While presence of the lubricant should reduce wear and transfer, it does not eliminate either entirely (*11*). The transfer method plus examining the lubricant for radioactivity should furnish the most sensitive method for comparing lubricants as regards their effectiveness in reducing metal-to-metal contact. Only when the surfaces are properly shaped and there is a copious supply of lubricant can complete separation of the surfaces and absence of solid contact by hydrodynamic action of a film of oil be obtained.

While on the subject of lubricants, a related field of investigation should be mentioned. This consists of introducing a radioactive tracer into the oil itself, generally as part of a chemically active radical and noting by the radioactivity where in the rubbing system or auxiliary parts it reacts or deposits. Clark, Gallo, and Lincoln (*18*) prepared a sulphurized oil containing radioactive sulphur and demonstrated the formation of a sulphur-containing film on specimens of various commercial bearing materials when exposed to the oil for various times at different temperatures. They did not identify the sulphur compounds. This is rather the inverse process to tracing where radioactive wear particles go in the oil. It is of interest in the study of the action of extreme pressure lubricants, "running-in" compounds and chemical polishing agents on the rubbing surfaces of gear teeth, piston rings, etc.

This paper has discussed principally the application of the tracer technique to metals. Metals are of primary importance in practical applications of bearing materials and wear resistant surfaces in machinery. Also the local "cold welding" hypothesis of Bowden seems most plausible in the case of metals. However, dry friction is a universal phenomenon of solids, and its true explanation will probably apply to metals and non-metals alike. The type of experiment described here should be applied to some of the main categories of non-metals. The vitreous and ceramic materials should be of great interest in spite of their relatively complicated chemistry. Initial experiments (*11*), in fact, showed evidence of copper being transferred to glass.

This account does not pretend to be exhaustive in covering either methods or materials. Many of the suggested experiments have actually never been tried. It does serve to show how a new tool can assist in experiments on an old well-known but unexplained phenomenon. More important though, the new tool can suggest many completely new experiments which had never occurred to workers in the field prior to its advent.

The original experiments on radioactive transfer (*11*) were made possible by a research grant from the Chrysler Corporation and work along these lines is continuing under the same sponsorship. Some of the work (*12*) was also sponsored by the National Advisory Committee for Aeronautics. The neutron irradiation of the steel specimens referred to in this paper was carried out by the Clinton Laboratory of the Monsanto Chemical Company under authorization of the U. S. Atomic Energy Commission. The author also wishes to acknowledge the helpful discussion of J. W. Irvine in the preparation of this paper.

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Isotope Techniques in Biochemistry — III

Critical analysis of isotope techniques in the study of intermediary metabolism, a branch of biochemistry in which isotope methods have made their most interesting and impressive contributions to the better understanding of life processes

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THE STUDY OF INTERMEDIARY METABOLISM involves the investigation of the chemical reactions that take place in living organisms. Since the individual atoms of compounds often have different metabolic pathways, it is necessary to study each part of a molecule separately. The availability of isotopes of all the elements of biological interest enables the research chemist to do just this.

The classical approach of Knoop, in which entire molecules (fatty acids) were labeled with phenyl groups, was a relatively crude forerunner of the isotope method of labeling, which derives its power as a tool not only from its "naturalness" but also from its ability to label the individual atoms in a molecule.

The reactions of the carbon atoms of metabolites have always been of greatest interest to investigators, but isotopic carbon in suitable concentrations has not been generally available until recently and most isotope studies have therefore involved indirect labeling, particularly with deuterium and heavy nitrogen. Almost all metabolic reactions leave some of the bonds in the substrate molecules unbroken, so that carbon-linked atoms can often be used to trace the atoms to which they are linked. The studies made in this way have been remarkably successful in elucidating the reactions of the carbon skeleton of compounds. Almost of equal interest, however, has been the disclosure of important and unexpected activity in the nitrogen and hydrogen atoms.

Some of the voluminous findings that have resulted from the application of isotopes to metabolic problems can be found in biochemistry texts, while the less clear-cut and later work must be sought in reviews and the current literature. The general approaches by which these results have been obtained and the considerations necessary in planning metabolism studies using isotopes are discussed in this paper. Three types of problems can be roughly distinguished:

1. The conversion problems—does an organism convert substance A to substance B?
2. The "pioneering" problems—a labeled substance is administered and the isotope sought in as many places and substances as possible.
3. The kinetic problems—isotope concentration vs. time is studied.

Conversion Problems

Problems of this type usually originate from examination of the formulas of compounds of biological interest, or are suggested by the results of other experiments. For example, the small difference in chemical structure be-

tween tyrosine and phenylalanine had led the biochemist to suspect that animals could convert one into the other. Growth studies showed that phenylalanine is an essential amino acid, whereas tyrosine is not. This and other data suggested that phenylalanine could be converted to tyrosine, but the evidence was essentially circumstantial. The conversion was finally and simply demonstrated by feeding a rat isotopic phenylalanine and isolating from its tissue proteins tyrosine with a high isotope concentration (*1*).

It should be recognized that this, and probably all other isotope experiments in intermediary metabolism, cannot tell us whether the observed conversion goes through some intermediate or directly. It is probable that a complex is formed between the phenylalanine and the oxidizing enzyme, and it may also be true that the phenylalanine is acetylated or incorporated into a protein before the conversion takes place. If an intermediate is believed to exist, it should be treated like any other possibility in a conversion problem.

Handicaps Limit Method

At first appearance, it might seem that this approach, allied with a sufficiently fertile imagination, could solve every problem in metabolism. Indeed, an impressive body of knowledge has already been amassed in this way, and the rate of accretion is rising. However, three severe handicaps exist which limit its application.

The first is the metabolic instability of many known and suspected metabolites, which results in their destruction or conversion before they reach the cells that conduct the reaction of interest. The second is the inability of some substances to cross cell walls. It seems likely that phosphorylated compounds, high molecular weight proteins and other large molecules cannot enter a cell without first being hydrolyzed. The third difficulty is found in the limitations of current methods of isolation, determination of purity, or isotope analysis.

The first difficulty can be met by working with the simpler organisms, which have no circulatory system, so that the labeled material can be applied directly to the active cells (or cell). Of course, extension of the results of such experiments to the higher organisms cannot be made with certainty.

Use of Large Isotope Dose

Another approach consists of administering a very large dose of isotopic material. Flooding the organism thus permits a sufficient amount of compound to reach the cells of interest. This technique is wasteful and suffers from the danger that abnormal results will be obtained because of harmful effects on the organism. There is also the possibility that some of the wasted metabolite will be converted to the expected compound through an alternate route, but through so large a number of intermediates that the significance of the experiment will be uncertain. For example, an attempt to flood an animal with C^{14}-labeled pyruvic acid would result in the quick appearance of radioactive carbon dioxide and the extensive incorporation of the latter into many compounds otherwise unrelated to pyruvic acid. It is clear that this type of experiment must be conducted with great caution.

To minimize the difficulty just mentioned, it is frequently useful to use slices of the tissue being studied. In this way, exposure of a metabolite to other tissues is avoided. This use of isotopes, however, does not mitigate the uncertainty inherent in all tissue slice (and homogenate) work, namely, the question of the quantitative importance of the discovered reaction in

the intact organism. Moreover, a negative answer cannot be considered conclusive because the experimental conditions are so abnormal.

Use of a Known Precursor

A technique that has proved useful in overcoming the first two handicaps mentioned earlier is the administration of a known precursor of the suspected precursor. An interesting example is found in the studies of Bloch and Rittenberg (*2*) of the role of pyruvic acid as an acetylating agent. The homologue of phenylalanine, γ-phenyl-α-aminobutyric acid, is excreted by rats in the urine as the N-acetyl derivative. To test the hypothesis that pyruvic acid furnishes the acetyl group, these investigators fed deuterio *alanine*, which is known to be converted to deuterio pyruvic acid. That this pyruvic acid then acetylates the unnatural amino acid is demonstrated by the presence of considerable deuterium in the acetyl group of the excreted material.

It was necessary to show that alanine does not itself take part in the "detoxication" reaction by condensation with any phenylketobutyric acid formed. This was done by feeding alanine containing excess N^{15}; practically no isotope excess was found in the isolated acetylamino acid. There is also the possibility that pyruvic acid is first converted to acetic acid, which then reacts with the foreign amino acid. This question was answered by the discovery that ingested deuterio acetic acid will acetylate *p*-aminobenzoic acid, whereas alanine will not. It was found, too, that deuterio pyruvic acid, fed in the same dose as alanine, gives rise to acetylphenylaminobutyric acid of only one-fifth the deuterium concentration in the acetyl group. This indicates that considerable but not complete destruction (or loss of deuterium by enolization) takes place before it can reach the acetylating tissues.

The third handicap to the use of the conversion type of problem is a complex of mutually dependent difficulties. In order to analyze an isolated substance for its isotope content, one must have more than a minimum amount of material. This requirement was discussed in detail in the first paper of this series.* Many compounds exist in organisms in such low concentration that a sufficiently large sample simply cannot be obtained. Sometimes the concentration is reasonably high but a good method of isolation is not available. Some substances may be too unstable to be isolated in sufficient yields. For some compounds, the methods of determining their purity require excessively large samples. There are some substances that can be isolated readily, but the degradation reactions currently available are not efficient enough for small samples to permit the exact location of the isotopic atoms.

Perhaps none of these difficulties is insuperable, but it seems clear that much of the future isotope work in metabolism will involve considerable research on just these matters alone.

Techniques Available

A number of techniques is available to the investigator who meets these problems. One method is flooding, in a manner similar to that mentioned earlier. By administering an unusually large amount of material, preferably to a tissue slice or homogenate, it may transpire that an unusually large amount of conversion product will be made.

Another technique is the use of detoxication mechanisms, as described in the discussion of the pyruvic acid acetylating reaction. A surprising number of substances that exist in low (as well as high) concentrations in an

* Nucleonics, Vol. 1, No. 1, 24 (1947).

animal can be made to appear in the urine by feeding a conjugating compound (*3*). This method has the special advantage that the animal is unharmed and can be used as its own control; moreover, kinetic studies can be made readily.

The investigator trying to raise his isolation yield should consider using larger or more animals as an alternative to improving his isolation procedure. The current ready availability and the low cost of most isotopes remove the restrictions under which the earlier workers labored.

Carrier Technique

A technique peculiar to isotope work is the use of a carrier. At the end of the metabolic period of an experiment, a large quantity of nonisotopic suspected conversion product may be added prior to isolation. This useful method is illustrated in a recently published note (*4*) which describes the synthesis of leucylglycine by rats. Two 180-gm rats were each injected with 40 mg leucine and 25 mg C^{14}-carboxyl-labeled glycine. After 10 minutes, 60 mg of *non*isotopic leucylglycine were injected, and after six minutes more the animals were killed. A longer period of time would have resulted in excessive conversion of the amino acids into proteins and other products. Various organs were pooled, homogenized with trichloracetic acid, and one gm of leucylglycine added to the nonprotein filtrate. The two carrier additions permitted the ready isolation of 185 mg of leucylglycine possessing a small but definite radioactivity. The use of an *in vivo* carrier here is interesting; the first addition probably diluted out from the cells some of the leucylglycine that had just been synthesized, thereby retarding its incorporation into larger peptides.

The carrier technique can also be used with compounds labeled with the stable isotopes, particularly with high concentrations of N^{15} or deuterium. While the use of radioelements permits greater dilution and, thereby, the addition of somewhat more carrier, the question of purity usually limits the amount that can be added safely. The isolated compound must be free of the original isotopic precursor to a remarkable degree in order to avoid obtaining a falsely positive result. In the example given above, the contamination of the dipeptide by the original glycine to an extent of only 0.04% would have accounted for the positive result.

Various types of purity checks, most of which have been discussed in the previous paper in this series, are available for isotope work. Not yet mentioned is the occasional situation where the suspected contaminant can be destroyed, without affecting the substance of interest. Either the remaining chemical or the decomposition products are then analyzed for activity. In the latter case, it is probably advisable to add a little carrier in order to ease the task of isolation and analysis. Even if both substances are destroyed, it may yet be possible to separate and analyze the decomposition products.

Still another technique is the isolation of a known conversion product of a substance difficult to isolate. If, for example, it is felt that some compound is converted to serine, the labeled compound may be administered and *glycine* isolated. Glycine, shown to be a conversion product of serine (*5*), is much more easily isolated than serine.

Pioneering Problems

Biochemistry, like physics, is still in a primitive stage. Physicists hurl subatomic particles at atoms and look for the collision products. In a similar manner, biochemists administer isotopic compounds and look for the

metabolic products. This sort of pioneering research has led to unexpected and fertile discoveries, such as the existence of metabolic dynamic equilibrium and the quantitative importance of transamination and carboxylation.

In principle, the pioneering problem is simple. Some isotopic compound, preferably multiply labeled, is given to an organism as a single dose or over a period of time and as many potential conversion products as possible are isolated. The choice of substances to be isolated must be the result of the conflict between hope or "intuition" and the effort necessary to develop isolation procedures. It is sometimes useful to run a preliminary experiment with a sample of high isotope concentration and then make a number of crude fractionations of the organism for isotopic analysis. In this way, the presence of a small amount of a conversion product in a large crude fraction can sometimes be picked up.

Interpretation of Results

Most pioneering studies have been made with very simple compounds, particularly with deuterium oxide, heavy ammonia, radioactive carbon dioxide and phosphate, and some N^{15}-labeled amino acids. The interpretation of the results of this type of experiment is frequently difficult, and much of their value lies in the experiments they suggest. The actual isotope concentration found in a given substance is in general the result of a number of factors:

a) the rate of synthesis
b) the nature of its precursors and their isotope concentrations
c) the rate of isotope exchange, if any (as by transamination, dehydrogenation, hydrolysis, etc.)
d) the organ from which it is isolated
e) the nature of the animal and its diet
f) the rate of incorporation into the complex in which it occurs, if any (amino acid into protein, glucose into glycogen, etc.).

It may be pointed out in this connection that the determination of the sequence of metabolic steps cannot safely be made simply by examination of isotope concentrations. If feeding isotopic A yields compound C with a certain isotope concentration, and isotopic B yields C with a higher isotope concentration, its does not necessarily follow that A is a precursor of B and B the direct precursor of C.

The biochemist who reads the now classical pioneering isotope work will be struck by the need for considerably more work in the same line, extending the experiments by the isolation of considerably more substances. There is a definite need to extend the work with fractionated proteins, as indicated in an important paper by Shemin and Rittenberg (*6*). Perhaps the recent work of the Harvard group on blood proteins will be of use here. Similarly, fractionation of the formed constituents of cells will doubtless supply valuable data. Cell fractionation has been possible for the last several years by the large-scale differential centrifugation method developed particularly by Claude.

The third type of problem in metabolism studies is the kinetic problem. This will be discussed fully in a later paper in this series.

Isotope Inversion

This approach, apparently hitherto unused, is similar to the inverse-isotope-dilution analysis method described in the previous paper of this series. Many organisms, particularly the lower ones, can be grown on a diet that contains an isotopic compound as its sole source of a particular element. For example, the mold *Neurospora* can be grown on heavy ammonia as its sole source of nitrogen. The N^{15} concentra-

tion in all its nitrogenous compounds is then known. Any sort of metabolism study can now be made, using the techniques described previously, but with *non*isotopic substances. In effect, inversion permits using N^{14} as the labeling isotope. If, for example, we wanted to demonstrate the conversion of indole to tryptophan in *Neurospora*, it would be necessary only to add ordinary indole to the heavy ammonia-containing medium, grow the mold, and then isolate its tryptophan. The presence of more N^{14} in the tryptophan than in the other nitrogenous substances indicates conversion.

The usefulness of this inversion is that nonisotopic precursors can be used, obtained either by the usual synthetic routes or by isolation from natural sources. The latter method is invaluable when the substance wanted cannot be synthesized at all. Additional considerations involved in the use of isotope inversion were discussed in the preceding paper in this series.

Use of Labeled Hydrogen

Many uses for isotopic carbon and the isotopes of the biologically rarer elements will present themselves to the investigator. The use of deuterium or tritium, however, requires special discussion.

Isotopic hydrogen can frequently be used as a label for carbon atoms, since many metabolic reactions do not affect all of the hydrogen-carbon linkages of many compounds. The value of this indirect labeling is attributable to the fact that it is usually considerably easier to synthesize compounds with isotopic hydrogen than with isotopic carbon. The extent of this difference will be made more evident in a later paper, in which problems in isotopic syntheses will be discussed.

The actual stability of a carbon-hydrogen linkage must be ascertained for the individual case. The rapid exchange with water hydrogen of the hydrogen attached to oxygen, nitrogen and sulfur is well known. The hydrogen on carbon atoms next to carbonyl groups tends to exchange moderately readily, as does the methylene hydrogen of glycine. Not only biological reactions but isolation procedures may wash out labeled hydrogen, and the effect of the latter must be determined. Labeling with hydrogen atoms in positions normally considered by organic chemists as "activated" is obviously dangerous.

Hydrogen Generally Stable

In general, the hydrogen in aliphatic chains and inactive aromatic rings is quite stable. Detailed studies have been made by Schoenheimer and Rittenberg of the metabolic stability of hydrogen-carbon bonds. A small degree of lability is permissible if the experimental period is not so long that an excessive amount of the isotopic hydrogen washes out. Metabolic labilization can sometimes be avoided by using tissue slices, which tend to conduct fewer reactions than a whole organism.

In practice, the reliability of hydrogen as a substitute for isotopic carbon can be checked by an analysis of the body water or the water of the culture medium. If the deuterium or tritium concentration in the isolated suspected conversion product is higher than in the body water, the conversion must have occurred.

Synthesis of the isolated compound from water (as its source of hydrogen) could not give a product with an isotope concentration higher than that of the water. On the other hand, a higher isotope concentration in the body water is not necessarily a negative result. This is so since oxidation of the administered precursor may occur much faster than its conversion. However,

the presence of a relatively huge amount of water in organisms makes such a situation unlikely. It is advisable to isolate the potential conversion product from the internal organs or growing organisms because these are metabolically very active.

The use of labeled hydrogen sometimes gives insight into the nature of intermediates. This can be done relatively easily by maintaining the organism in heavy water or tritium oxide. This is essentially the inverse-isotope technique. If a compound containing stably bound deuterium is isolated, it may indicate that a precursor had existed that contained a labilizing group. Other interpretations are possible, for the hydrogen of body water can enter compounds in several ways. All substances that are formed by reduction, as fat from sugar, will be found to contain hydrogen atoms from the *milieu* water. Isotopic hydrogen can also be bound to carbon by the addition of water to a double bond, as in the biological conversion of fumaric to malic acid. Compounds formed by condensation of fragments containing labeled hydrogen will also be labeled.

Example of Method

An interesting illustration of this approach is found in some recent work on liver glycogen (*7*). Administration of heavy water resulted in the production of glycogen containing deuterium. Since the glycogen made by polymerization of dietary glucose will contain no isotopic hydrogen, a certain fraction of the glycogen must have been made from compounds that had obtained hydrogen from the body water. Several of the 3-carbon fragments in the glucose degradation system pick up hydrogen from the body water, by reduction and hydration, so that reversal of the degradation reactions would result in the appearance of isotope in the liver glycogen. Apparently this reversal accounts for an appreciable fraction of the liver glycogen. This is indicated also by the finding that a higher deuterium concentration is obtained when lactate is fed instead of sugar.

Together with another isotopic label, preferably carbon, isotopic hydrogen is extremely useful in demonstrating the quantitative importance or existence of reversible dehydrogenations. By comparing the ratios of the two isotope concentrations, before administering and after isolating, an estimate can be made of the degree of hydrogenolysis. The reactions of molecular hydrogen with biological systems have been studied with deuterium (*8*).

The investigator should avoid high concentrations of deuterium in body water for there seems to be an appreciable effect on the velocity of reactions. The definite abnormalities that result from sufficiently high concentrations have been well publicized.

One more good word for isotopic hydrogen: Heavy water is quite cheap, and if necessary, can be determined with cheap equipment, such as the falling-drop apparatus. Unfortunately, this method of analysis requires large samples, of the order of 100 mg of water. The mass spectrometer will work on one milligram of water.

Use of Heavy Nitrogen

As with hydrogen, the use of nitrogen for labeling compounds or individual carbon atoms frequently permits much easier syntheses than the use of isotopic carbon. The actual stability of the linkage must be determined in the individual case, and a test similar to the body water test for hydrogen can be applied. If aminoid nitrogen is released from carbon entirely, it will appear in the highest concentrations in the body ammonia, amides, and certain amino acids.

For example, when D-leucine, labeled

with deuterium on the carbon chain and with N^{15} in the α-position, is fed to rats and the rats subsequently killed and fractionated, it is found (*9*) that the highest N^{15} concentrations occur in the urinary ammonia and urea and in the protein amide nitrogen (mostly glutamine), glutamic acid, aspartic acid, and arginine.

Most of the N^{15} in the arginine is in the amidine group, which appears to be involved in the synthesis of urea. Other amino acids contain some N^{15}, but to a lesser extent, apparently by utilization of the ammonia from the completely deaminated D-leucine. That the carbon chain of the leucine is reaminated to the L-isomer is apparent from the presence of considerable deuterium in the protein leucine. When the similarly labeled *normal* isomer of leucine is fed (*10*), however, the highest N^{15} concentration is found in the protein bound leucine, with ammonia and urea next highest but somewhat lower. Glutamic and aspartic acids are next highest.

In other words, a considerable amount of the labeled nitrogen is retained by the leucine molecules. Judging by the change in isotope concentration ratios, more than one third of the labeled nitrogen is replaced by ordinary nitrogen during the period of the experiment.

For an especially interesting application of this data and approach, see the proof of the utilization of glycine for hemin synthesis (*11*).

Similar distribution information is being worked out for carbon dioxide now, so that criteria for directness of conversion will soon be available for users of isotopic carbon.

Choice of an Isotope

When the metabolic fate of an individual atom is being studied, some isotope of that element must be used (except when H, N, S, or O is being used to label a carbon atom). For some elements, there is at present no choice. Oxygen, nitrogen, sodium, potassium, chlorine, phosphorus and the trace elements are normally available in only one isotopic form. (Actually, of course, two or more different isotopes are present, but only one of these is considered the tracer). Hydrogen, carbon, sulfur and iron can be obtained in two or more isotopic varieties. Additional elements can probably be drawn into this group by sufficient demand.

The use of a radioactive isotope introduces a certain amount of danger to the biochemist and some uncertainty as to whether the experimental organism has been appreciably affected by the radiations. The former point can be negated by exaggerated care until the actual toxicity can be determined, while the latter can be checked by cytological examinations or by the more tedious method of repeating the experiment at another level of activity and comparing the results. A repetition with a stable isotope is often useful.

Comparison of Advantages

If precise quantitative results are desired, stable isotopes are preferable because the mass spectrometer is more precise than radiation-measuring devices by a factor of about 5. If a high dilution is expected, the radioelements should be used, because Geiger-Müller counters and ionization chamber electrometers can quantitatively detect very much smaller isotope concentrations than can the mass spectrometer. In this connection, the warnings given in this and other papers on the need for high purity should be considered carefully.

If it is desired to use very small samples for isotopic analysis, radioactive elements will usually be preferred. Microgram samples can be analyzed, provided the specific activity is sufficiently high. This characteristic is of

special interest because of the increasing success of the paper chromatography and other counter-current methods of separation.

When an isotopic compound is wanted, but is difficult or impossible to synthesize, it is sometimes useful to prepare it by biological synthesis, that is, by administering some isotopic precursor to an organism and then isolating the desired substance. Frequently, considerable dilution with other, unlabeled precursors occurs and it is therefore advisable to use either very high concentrations of the stable isotopes (mainly deuterium, which is available 99.8% pure) or the radioactive isotopes, which can stand the dilution quite easily.

Long-term investigations require radioelements with long half-lives, especially when long and tedious syntheses or isolations are involved. If a very fast experiment is to be performed, certain short-lived isotopes can be used, such as C^{11}, N^{13}, and F^{18}. These possess very penetrating radiations and can be obtained in high concentrations, so that considerable dilutions are practical.

When all or most of a molecule is being labeled, or an alternate for isotopic carbon is being considered, it is useful to estimate which impurities will be found in the sample that will be analyzed. An element should be chosen for labeling that will not occur in the contaminants. For instance, the presence of glutamic acid in cystine that is being analyzed for its sulfur isotope content will have no effect. In this way it is sometimes possible to isolate rather crude preparations, determine their content of the element of interest, and then determine the activity of the samples. From this the specific activity of the element can be calculated. If a stable isotope is used, the sample need not undergo an elementary analysis, since the isotope ratio is given directly by the mass spectrometer.

Other choice considerations have been given in the course of other discussions. The next paper in this series will discuss the kinetic approach to the study of intermediary metabolism.

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GENERAL RULES AND PROCEDURES CONCERNING RADIOACTIVE HAZARDS

LABORATORIES CONDUCTING WORK with radiomaterials need the most effective health-safety practices they can devise. To that end, these general rules are offered to guide officials responsible for initiating specific regulations in their laboratories.

The rules presuppose that laboratories so engaged will have access either directly or indirectly to the services of adequately trained technicians who will supervise health monitoring and accept responsibility for conformation with health-safety practices.

To laboratories seeking solution to special health-protection problems, the Isotopes Branch of the Atomic Energy Commission at Oak Ridge offers advisory assistance. In addition, the expert services of technicians in the Advisory Field Service and Technical Sections are available for field consultations where this may be desirable.

Compiled from "Standard Safety Requirements," A.E.C. Regulation, Safety No. 3, these are the precautions in effect at A.E.C. laboratories:

A. Tolerances (Maximum Permissible Exposure)

1. The tolerance level for total or limited body exposure is 0.1 rem (roentgen-equivalent-man)* in any 24-hour period. No individual shall knowingly expose himself or cause others to be exposed to greater than this quantity in any 24-hour period. It is advisable, however, to strive for the lowest possible daily total exposure in every operation.

   The 0.1 rem represents the total additive exposure from the independent components of all radiation involved. The relationships between r (roentgen),* rem (roentgen-equivalent-man),* and rep (roentgen-equivalent-physical)* in accordance with present data are considered as follows:

Radiation	*roentgens*	*rem*	*rep*
X-ray	0.1	0.1	0.1
gamma	0.1	0.1	0.1
beta	—	0.1	0.1
alpha†	—	0.1	0.01

2. Tolerance level for beta and gamma emitters:
   a. *Air contamination:* The tolerance level for the most hazardous and common beta-gamma radioisotopes (such as iodine, strontium, barium, etc.) is considered to be about 10^{-7} microcuries/cc of air. If one takes the overall collection efficiency of the precipitron‡ (operating at 11.5 cu ft/min) and the counter (Eck and Krebs feeding into a scale-of-64) to be one-half per cent, this would correspond to about 10,000 counts per minute (cpm) for the collected sample. Therefore, the general rule is to evacuate an area when the counting rate exceeds 10,000 cpm and to wear masks when the counting rate exceeds 1,000 cpm.
   b. *Water contamination:* (The tolerance level in water for these beta-gamma radioisotopes is considered to be about 5×10^{-4} microcuries/cc of water. This would correspond to about 1,100 disintegrations per min (dpm) per cc (*ca.* 150 beta cpm/cc for counters used by the technical division).
   c. *Surface contamination:* (As measured with a "standard" counter, or 3¼ in. from a thin-walled Eck and Krebs counter approximately 0.005 in. thick

* See Appendix A for definition of terms.
† Considered from the standpoint of internal effects only.
‡ See Appendix B for description of equipment.

Tolerances (Maximum Permissible Exposure)

Item	*Instrument*	*Tolerance level*
Clothing, table tops, body, etc.	Eck and Krebs counter	500 cpm
Hands	Eck and Krebs counter	700 cpm
Smear test on table tops, floors, equipment, etc.	2 sq in. filter paper smear over 12 sq in. counted with β and γ counters	200 cpm of β and γ
Boxes for shipment by air or rail	Electroscope	β and γ less than 15 mr at the surface of package.
All laboratory and operating areas	Electroscope, C. P. meters, etc.	All areas with radiation 12.5 mr/hr shall be roped off and have signs posted
Shoe (outside)	Foot counter	30 scaler units = 10,000 cpm $\cong$ 14 mr/hr of β and γ
Shoe (inside)	Shoe probe	1,000 cpm $\cong$ 1/3 mr/hr of β and γ
Clothing	Laundry counter	500 cpm $\cong$ 1/3 mr/hr of β and γ
Thyroid	C. M. Probe counter	800 cpm with counter against throat ($\cong$ 1,000 mr/24 hr in thyroid)

with approximately 5.4 cm^2 flat-plate area.)

B. Radiation Monitoring

1. Instruments to be used for surveys will be distributed and maintained in calibration by trained personnel.
2. Personnel Monitoring Instruments*
   a. Two pocket chambers* and a film badge meter* are to be worn by everyone who goes within the radiation area, except visitors, who will wear a film badge meter.
   b. Pocket chambers and film badge meters are not to be tampered with in any way, and are to be used only for personnel monitoring. If a meter is accidentally broken or a cap comes off, it should be returned at once to the point of distribution and a new meter obtained.
3. Immediate investigation of high pocket-meter readings and of high hand and foot counts shall be made by the supervisor of the person concerned and all data recorded.
4. When an individual, with the aid of his supervisor, is unable to reduce a count below tolerance limits, he shall report to the responsible physician as soon as practical, in any instance before leaving the laboratory.

C. Protective Clothing and Devices

1. Clothing
   a. It shall be the responsibility of the individual and/or his supervisor to see that appropriate protective clothing is worn whenever clothing contamination is probable (laboratory coats, coveralls, etc.)
   b. Coveralls, laboratory coats or other protective garments worn in the restricted area are not to be

* See Appendix B.

worn in the cafeteria. This applies to all personnel. Protective clothing worn outside the restricted area in connection with work where radioactive contamination is possible shall be governed also by this rule.

2. **Gloves**
   a. Suitable gloves shall be worn whenever hand contamination is probable. Surgical gloves will not stop penetrating beta particles, hence remote handling with tongs and sufficient glassware shielding is necessary in working with strong sources of energetic beta emitters. Surgical gloves can, however, eliminate deposition of active material on the hands.
   b. Surgical technique (see Appendix C) shall be used when putting on and removing surgical gloves, in order to avoid the possibility of contaminating the inside surfaces.
   c. Rubber gloves are to be washed and cleaned, if practical, before removal. All rubber gloves are to be stored and handled so as to prevent contamination of the inside surfaces.
   d. Care shall be exercised when using organic solvents to avoid skin contact with radioactive material. (Solvents may make the skin more permeable.)

3. **Respirators, combat mask or air line hoods**
   a. An approved respirator, combat mask or air line hood shall be worn in any location where the concentration of air-borne beta and gamma emitters may be greater than 10^{-8} microcuries/cc.
   b. It shall be the responsibility of the supervisor of the area using respirators to see that these are not used more than once before being sent to the contaminated-article laundry for monitoring and cleaning (if necessary).
   c. Combat masks and air line hoods (complete sets) shall be monitored and inspected after each use and at two-month intervals when not in use.

4. **Equipment and Fixtures**
   a. Hoods in which plutonium (or hazardous beta-gamma material) is actively handled shall be provided with nonporous, inert floors, such as glass, tile or metal; preferably a stainless steel tray should be used to catch possible spills. All work with plutonium, even dilute tracer solutions, shall be done over such surfaces or over heavy kraft or blotting paper to minimize danger from spills. All working surfaces should be of such nature as to be easily decontaminated [nonporous or readily replaceable (kraft paper)].
   b. Meticulous care should be taken to see that the moving parts of open centrifuges are maintained free of contamination. Covers of centrifuges handling active materials must not be open while the motor is in motion.
   c. Equipment and laboratory-ware contaminated with plutonium (or hazardous beta-gamma material) shall be stored in an operating hood or under water until cleaned.

D. Eating and Smoking Rules

1. Eating, storing or preparation of food in a laboratory or operating rooms where active materials are handled is forbidden. The use of milk bottles or other food containers in handling or storing chemicals is forbidden.
2. Smoking must be controlled by local area rules; that is, smoking permitted in certain uncontaminated areas. One of the greatest dangers of smoking is contamination of the cigarette (pipe, etc.) with activity from contaminated hands.

E. Contamination of Persons

1. Hand and Shoe Contamination—General
   a. All persons, while working with radioactive materials wherein detrimental hand or shoe contamina-

tion is possible (as determined by supervision or upon advice of local area Health Physics representative), are to:

(1) Keep the fingernails cut short

(2) Wash hands thoroughly before eating, smoking or leaving the work area for any purpose

(3) Refrain from smoking

(4) Wash rubber gloves if practical before removing them from the hands

(5) Utilize available hand and shoe counting facilities as frequently as necessary to insure decontamination. (Adjacent to each counter which is reserved for hand and shoe counting there will be a record sheet on which the individual is to record all counts taken, including high counts and those after washing.)

(6) Report to supervision any hand or shoe count which is above the specified limiting value marked on the counting machine. (If the individual, with the aid of his supervisor, is unable to reduce the count below the limiting value listed on the counting machine, Health Physics or the Medical Department shall be notified as soon as practical, and in all instances before the individual leaves the plant at the end of the shift.)

(7) No work with plutonium* in any chemical or physical form is ever to be done by a person having a break in his skin below the wrist or with a bandage on his hand. Any person receiving a puncture wound suspected of hazardous radioisotope contamination shall report to the doctor at the dispensary immediately.

2. Ingestion, Inhalation, Injection
   a. The pipetting of active solutions by mouth is *forbidden*. Glass-blowing in laboratories containing active materials should be discouraged.
   b. Any person who knowingly swallows, inhales or receives an injection of a radioactive material or who may have been overexposed to radiation from any source is to report to the Medical Department at once.

F. Contamination of Areas

1. All areas in which there is radiation in excess of 12.5 mr/hr either shall be roped off with appropriate signs posted to prevent persons from coming dangerously close to the radiating source, or, where the hazard is of a permanent nature, shall have permanent signs posted, barricades installed and existing doors locked. Where activity levels are very high, a patrol force guard should be posted to prevent accidental overexposure.
2. Experimental work involving especially hazardous levels of activity shall not be undertaken until suitable protective measures have been agreed upon by the section chief or chief

* All rules pertaining to work with "plutonium" apply to work with other radioisotopes that present a similar health hazard (1 microgram Pu ~ 1/6 microcurie.)

Maximum Contamination Levels

	Surface: dpm for 150 sq cm (small spots)	*Smear: dpm for 2 sq in.,* counted in standard chamber*	*Total Contamination: dpm/sq ft (large area)*
Exposed surfaces, floors, bench tops, etc.	2,000	0	14,000
Exposed but protected from handling (roped off, etc.)	10,000	25	7,000
Inside poor or intermittently used hood	30,000	25	280,000
Inside adequate hood, operating	(upper limit will vary with area rules and hood efficiency)		

* A 2 sq in. paper wiping a total of 12 sq. in. of tested surface yields a test sample.

supervisor in charge and the Health Physics section chief.

3. In case of any permanent change of personnel or permanent vacating of quarters, it shall be the duty of the individual and his supervisor to see that the area is properly surveyed and if necessary, decontaminated before it is vacated.
4. Areas or rooms which are to be kept free from contamination are to be posted with signs on all doors warning persons not to enter with contaminated materials or clothing.
5. A hood containing a high amount of plutonium contamination must be clearly marked "high-level hood." Hoods so designated shall not be repaired or worked on without approval of Health Physics, which shall specify protective measures for the personnel involved.
6. **Spills and contamination levels**
   a. No exposed plutonium is ever "tolerable;" the table on the previous page gives maximum levels which are perhaps unavoidable in some cases.
   b. All spills of plutonium must be cleaned up immediately unless inside of adequate hood. Cleaning responsibility shall lie with the operating group in the room and area involved, and they shall check after cleaning to verify that cleaning is thorough. In cases of large spills or if in doubt, call a Health Physics representative.

G. Storage, Handling and Disposal of Radioactive Materials

1. **Storage and handling of plutonium or similar hazardous substances**
   a. Quantities of plutonium greater than 1 microgram shall be securely covered during storage and kept in a hood equipped with doors, or in other spaces specifically accepted by the Health Division Director, or his representative, as suitable under the given circumstances. (Such as shelves constructed in an outpocketing from existing hoods or separate boxes equipped with doors and vented to a proper exhaust.)
   b. All transfer of materials between hoods and storage devices must be done in such a manner as to avoid the possibility of spillage or breakage. Double containers to eliminate contamination and breakage danger should be used.
   c. Any work with materials susceptible to atmospheric distribution of plutonium (that is, dusting, spillage, vaporizing, effervescence of solution, etc.) shall be done in an "adequate hood." (See Appendix A for hood specifications).
2. **Disposal of materials contaminated with plutonium or similar hazardous substances.** All discarded material which has been liable to plutonium contamination is to be buried. Distinctive cans are to be provided, and these handled with proper discretion. If a dust hazard is involved, a Health Physics representative shall accompany the can when it is taken to be buried to see that respirators and protective clothing are used when needed. In rooms where large (1 to 2 microgram) amounts of plutonium are handled, a small red closed can should be provided with a paper lining to receive waste of known contamination, so that the closed paper lining may afford some measure of protection against spread at the time of disposal.
3. **Transportation of Active Materials**
   a. **Off-Site Shipments**
      (1) Shipment of material by rail or air express must conform with the regulations of the carriers governing transportation of radioactive material.
      (2) Sufficient protective means for material shipped by special truck or car shall be used to prevent radiation levels greater than 50 mr/hr at the rear wheels of the truck or car and to prevent levels at the truck cab or driver's seat of a car in excess of 100 mr/day for any persons in the car or cab.
      (3) If material is shipped in solution, the vessel containing the solution

is to be enclosed in a metal container with a sufficient absorbent material to take up all the liquid in case of breakage of the vessel. The container shall be equipped with a gasketed top. The top should be so constructed that the least amount of exposure is received in removing either the top or the solution. No package shall bear contamination on the outside surface above that specified in Section F 6 for alpha emitters and 500 cpm for beta emitters, as determined from smear tests using standard procedures established by the Health Physics section.

b. **On-Site Shipments or Transfers**

(1) Transportation of active material within or between buildings on the plant must proceed in a manner which will cause no overexposure to any part of the body and will prevent a spill of active solutions.

4. **Disposal of Active Trash, Unwanted Active Materials or Equipment**
   a. Two trash cans painted entirely red (both top and can) are to be provided at each desired location for trash which is contaminated.
   b. Only *one* of these two cans should be used at a time and the one in use should be tagged by Supervision of the Area—"*Use This Can.*"
   c. It shall be the responsibility of Supervision to see that these cans are monitored at sufficiently frequent intervals to prevent active materials from accumulating to such an extent that radiation levels of greater than 12.5 mr/hr occur.
   d. Once a can has been labeled "*Driver, O.K. to Pick Up,*" no more contaminated trash shall be put in that can. When the can has been emptied and returned, Maintenance should remove the tag so that it may be held in reserve while the second can is in use.
5. **Burying Ground.** All contaminated material and equipment that is to be discarded shall be thrown only in the trenches provided for that purpose.
   a. Sufficient earth must cover active materials in a trench to keep the level of radiation at the top of the trench below 12.5 mr/hr.
      (1) Keep sufficient earth over trash to prevent trash from being blown or floated outside the trench.
      (2) Keep an adequate record of all equipment taken to the burial ground for burial or for storage.
   b. The burial ground will be periodically surveyed.

H. Summary of Responsibilities for the Enforcement of Radiation Rules

1. No individual shall knowingly expose himself or cause others to be exposed to more than 0.1 rem in any 24-hour period.
2. In extreme emergencies the acting area head may assume responsibility for a person exceeding 0.1-rem daily exposure provided that:
   a. Insufficient time exists to obtain the services of the Health Division for consultation.
   b. A written report is submitted within 24 hours to the Plant Director and to the Health Division Director, covering the details concerning the necessity for and the amount of the overexposure, and the precautions taken.
   c. The individual or individuals so exposed are sent to the Medical Department as soon after exposure as possible. The Supervisor of each area shall delegate the above authority in his absence.
3. **Supervisor's Responsibilities re: Personnel Monitoring Meters**
   a. To see that all persons while working in the restricted area wear meters at all times.
   b. To see that persons working with active materials outside the restricted area wear meters while so engaged.
   c. To request the issuance of permanent meters for employees going into restricted areas on an average of more than 3 days per week.
4. **Supervisor's Responsibilities re: Protective Clothing**
   a. It shall be the responsibility of the individual and/or his super-

visor to see that appropriate protective clothing is worn whenever clothing contamination is possible.

b. It shall be the responsibility of the supervisor of the area using respirators to see that these are not used more than once before being sent to the laundry for inspection and cleaning.

c. It shall be the responsibility of the supervisor of the area using combat masks and air line hoods to notify the area Health Physics representative after each use.

5. **Miscellaneous**

a. Supervisors are responsible for maintaining safe radiation levels at the boundaries of their own areas of assigned locations.

b. Each area head or section chief shall be held responsible for maintaining recorded surveys of all radiation hazards in the area.

c. In case of permanent change of personnel or permanent vacating of quarters, it shall be the duty of the individual and his supervisor to see that the area is properly surveyed and, if necessary, decontaminated before it is vacated.

d. It shall be the responsibility of the supervisor of an area to see that the active waste-disposal cans are monitored at sufficiently frequent intervals to prevent active materials from accumulating to such an extent that radiation levels of greater than 12.5 mr/hr occur.

e. The supervisor shall see that the top of the burying-ground trench in which trash is thrown does not exceed 12.5 mr/hr.

APPENDIX A

Definition of Radiation Terms

Roentgen (= r) is that quantity of X or gamma radiation such that the associated corpuscular emission per 0.001293 gm of air produces in air ions carrying 1 esu quantity of electricity of either sign.

Roentgen-equivalent-physical (= rep) is that quantity of ionising radiation which is capable of producing 1.615×10^{12} ion pairs per gram of tissue or that will suffer an absorption in tissue of 83 ergs per gram.

Roentgen-equivalent-man (= rem) is that quantity of radiation which when absorbed by man produces an effect equivalent to the absorption by man of one roentgen of X or gamma radiation.

APPENDIX B

Personnel Monitoring Meters

The Victoreen Pocket Meter is a small air ionization chamber or air condenser. It has a full-scale reading of 200 mr when charged and read on the minometer in use at Clinton Laboratories. When it is carefully used, it usually gives an error less than 5% of full scale. It is charged at 143 volts and does not give saturation errors unless subjected to extremely high fluxes (of the order of 10 mr/second). It has a bakelite wall thickness of 0.172" and so cannot be used for beta-ray measurements if the energy is less than one Mev.

The minometers are calibrated with 200-kv X-rays so that the pocket meters read low by about 20% for radium gamma rays (1.8 Mev). The meters will discharge, giving "false readings" when given extremely rough treatment or dropped.

The Badge Meter or Film Meter contains an open window and a cadmium shield. A dental-size film packet holding two films, one a sensitive (0–5 r) and the other an insensitive film (0–20 r), is placed in this meter by the personnel monitoring girls of the Health Physics section.

The open window may give an indication of the beta exposure but is difficult to interpret if low-energy gamma radiation is mixed with the beta rays because the film is 20 times more sensitive to low-energy X-rays (energy 20 kv) than it is to gamma rays. The readings made behind the cadmium shield are reliable for gamma-ray energies down to about 70 kv.

Film Rings can be used with any of the films described above. They may be obtained by a request to any of the Health Physics surveyors. They have a very thin (0.004") beta window and some of them are provided with a cadmium shield.

Dose Meters may be obtained by a request to any Health Physics surveyor. They are available in the self-charging type or the externally charged variety. They have ranges up to about 200 mr. Their limita-

tions are essentially the same as those of the Victoreen pocket meters.

Precipitron is an instrument for monitoring the activity dispersed in air as dust, etc. As used on the Project, it is a slightly modified form of the electrostatic dust collector manufactured by the Union Mines Corporation.

The modifications may consist of a larger air circulation motor and the insertion of a suitable removable sleeve in the cylinder in order to remove collected dust for radiation monitoring.

APPENDIX C

Surgical Technique for Putting on and Removing Rubber Gloves: Surgical rubber gloves, used during procedures where hand contamination is probable, should be prepared in advance by powdering the insides and by folding out the wrist portion of the gloves to form a cuff of about two inches.

To put on the gloves the following procedure is advised:

1. The hands are powdered well with talc.
2. The first glove to be donned is grasped at the folded cuff, without touching the exterior of the glove, and pulled onto the fingers and hand, leaving the cuff in the folded position.
3. The second glove is lifted by inserting the fingers of the gloved hand beneath the cuff, and pulling it onto the bare fingers and hand.
4. The cuffs of both gloves are turned back over the wrists, without touching the bare skin.
5. The loose fitting glove fingers are then "worked" into position in the same manner as are cloth gloves.

Removal of the gloves is accomplished in the reverse order:

The fingers of one gloved hand grasp the beaded rim of the top of the glove of the other hand without touching the inside of the glove and, by traction, invert the glove and pull it off the hand. The index finger of the bared hand is now inserted beneath the beaded rim of the top of the other glove and, without contacting the exterior surface of the glove, it is inverted and pulled off the hand.

APPENDIX D

Recommended Procedure for Washing and Decontamination of Hands:

1. Wash thoroughly for two to three minutes by the clock with a teaspoonful of Lan-O-Kleen Soap, using a sufficient amount of tepid (not hot) water to maintain a thin paste, and rub the paste over the entire surface of the hands and fingers. Rinse off completely with water and repeat the process at least three times.
2. If the above procedure is not enough to remove all dirt and contamination, the hands should then be scrubbed for a period of at least eight minutes by the clock with a liquid or cake soap, hand brush, and tepid water, being sure to brush the entire surface of the hands, especially around the nails and between the fingers. Light pressure should be exerted on the brush—do not press so hard that the bristles are bent out of shape. Eight minutes is usually a sufficient time to allow three complete changes of tepid water and soap. Each one of these three washings should be so thorough that the brush will cover *all areas* a minimum of four strokes. A convenient routine is to start by scrubbing one thumb, being sure to brush all surfaces, proceed to the space between the thumb and first (index) finger and similarly to each finger and the webbs between the fingers. Attention should be given to the palm and back of the hand and final additional scrubbing of the nails and cuticles before proceeding in the same manner with the other hand.
3. Lanolin or hand creams may be used after washing to soften the hands and prevent chapping (keeps cracks from forming through which active material might be absorbed).
4. Additional Method of Decontamination for Fission Products Generally: *Titanium Dioxide Paste* (TiO_2). The material should be made up as a paste or slurry and kept wet with plain or distilled water. It should be applied to the hands as the paste and thinned with tap water while washing. A minimum of 2 minutes of thorough application of this lather to all hand surfaces, especially about the finger nails, is recommended. It should then be thoroughly rinsed off with luke-warm tap water, and followed by a thorough washing with soap and water and a hand brush. If any of the paste is left under the nails after washing, it will form a rather hard cake that is difficult to get off later.

BIBLIOGRAPHY
GEIGER AND PROPORTIONAL COUNTERS

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THIS BIBLIOGRAPHY was prepared in large part during the summer of 1947 for the use of the Electronics Division, Brookhaven National Laboratory, Upton, New York. These references were selected on the basis of their value to workers newly engaged in nucleonic instrumentation. The balance of this list, containing references on subjects related to counters, will be published in subseqent issues.

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NUCLEONIC EVENTS

AEC OFFERS HOME TO BAR HARBOR INSTITUTION

The United States Atomic Energy Commission has offered to provide funds, buildings and equipment for the re-establishment at Brookhaven National Laboratory, Patchogue, L. I., of the Roscoe B. Jackson Memorial Laboratory of Bar Harbor, Maine, destroyed in recent Maine forest fires.

The famous cancer research center, which has a staff of 40, lost nearly all records and equipment in the forest conflagration. The offer of a building and equipment for the laboratory and of temporary housing for a part of the staff has been authorized by the Commission. The AEC has funds immediately available for this purpose from the authorization in its appropriation of the current fiscal year to spend up to $5,000,000 to assist cancer research outside of the AEC program.

Shields Warren, director of the AEC Division of Biology and Medicine, and Philip B. Morse, director of Brookhaven National Laboratory, said the research program directed by Clarence C. Little, director of the Bar Harbor institution, and an outstanding research worker in the hereditary aspects of cancer, was directly related to the cancer research program authorized for Brookhaven.

The research program of the institution, founded by the late Roscoe B. Jackson of Bar Harbor, is supported by funds from the American Cancer Society, from the United States Public Health Service, and from private sources. In addition to its cancer work, the Jackson Laboratory is the nation's foremost research institution in the field of pure genetics and its location at Brookhaven would substantially aid the AEC program of study of the genetic effects of radiation. The Jackson Laboratory, if moved to Brookhaven, would retain full independence, receiving only assistance and services from Brookhaven.

CONFERENCE TO DISCUSS RADIOISOTOPES IN AGRICULTURE

"The Use of Radioactive Isotopes in Agricultural Research" will be the subject of a three-day conference to be held by the Alabama Polytechnic Institute December 18–20 at Auburn, Alabama. Held in cooperation with the Oak Ridge Institute of Nuclear Studies, the meeting will bring together, through special invitations, scientists primarily from the southeastern states.

The program will include: "Techniques of Tagged Atom Research," W. A. Arnold, Clinton National Laboratory, Oak Ridge; "Radioactivity and Radioisotopes," Fred Allison, Alabama Polytechnic Institute; "Isotopes Available for Research," Paul C. Aebersold, AEC, Oak Ridge; "The Measurements of Radiations by Various Methods," Paul W. McDaniel, AEC, Washington, D.C.; "Protective Precautions in the Handling of Radioactive Materials," G. William Morgan, AEC, Oak Ridge; "Contributions of the Atomic Energy Commission to Agricultural Research," John C. Franklin, AEC, Oak Ridge· "Agricultural Research With Radiophosphorus," S. B. Hendricks, Bureau of Plant Industry, Beltsville, Maryland; "Studies of Chlorosis Using Radioactive Phosphorus and Iron," Orlin Biddulph, State College of Washington; "Agricultural Research With Radio-

active Sulfur and Arsenic," M. D. Thomas, American Smelting and Refining Company, Salt Lake City; Demonstration of a typical tracer experiment, Wendell C. Peacock, Clinton National Laboratory, Oak Ridge; "Atomic Energy Radiations and Plant Mutations," S. J. Sadler, University of Missouri; "Use of C^{14} for Tracer Research," Howard B. Skipper, Southern Research Institute, Birmingham, Alabama; "Nutrition Studies with Radiocobalt," J. G. Davis, University of Florida; and topics to be selected by G. Harold Copp, University of California.

RADIOMATERIAL CARRIER APPLIES FOR ICC LICENSE

The first application for authorization to transport radioactive materials was recently made to the Interstate Commerce Commission. Examiner Richard J. Flood, Jr., recommended that ICC grant to the W. J. Dillner Transfer Company, Pittsburgh, authority to transport radioactive chemicals, materials, drugs and medicines requiring special handling, and equipment, containers, instruments and apparatus, between all points in the United States. Flood reported that apparently there are no other motor carriers engaged in this service.

The Dillner Company's application was supported by the Westinghouse Electric Company and the Atomic Energy Commission. A Westinghouse official testified that the company expected to manufacture radioactive materials in Pittsburgh and desired Dillner's service for shipment to all points. AEC's Oak Ridge traffic manager said that agency wanted Dillner's special equipment available as an alternative to air transport of radioactive materials, principally for medical use.

The Dillner Company is planning to construct special semitrailers insulated with lead and other substances to prevent harmful radiations. The operation would require a big capital outlay because, for one thing, the equipment would be of little use in hauling other commodities, and could not be used continuously in transporting radioactive materials as a lapse of time would be necessary to dissipate the energy absorbed by the vehicles.

The ICC examiner reported lively interest in chemical research for the use of radioactive substances for trade purposes. The first line of commercial activity is in the hospital trade. The largest present use of radioactive materials is in treating various diseases, including cancer.

Value of radioactive shipments would be high. The examiner estimated that a half million dollars' worth could be carried in a single truck. He quoted a Koppers Company research consultant as saying the best way to transport this material would be by truck, loaded at point of shipment and not removed until it reaches the destination.

Safety regulations governing transportation of radioactive materials will soon be issued by the ICC.

FRENCH PHYSICISTS BUILD PROTON MICROSCOPE

Atomic physicists at the College de France in Paris have built the first experimental proton microscope, and have under construction a second much larger one. It is hoped that this new advance will extend the range of possible magnification eventually to 1,000,000 diameters, although the new four-lens 3,000,000-volt proton microscope being built will be limited to 600,000 diameters. Top possible range of light microscopes is 3,000 diameters, and of electron microscopes 100,000 diameters, according to Claude Magnan, assistant director of the College de France's laboratory of atomic physics and co-developer of the new instrument.

The proton microscope is built on

the same principle as the electron microscope, except that protons are used to bombard the object to be photographed instead of electrons. An absolutely steady stream of protons has to be used, and such streams have recently become available as a result of work in the United States and Germany on the spectrography of masses.

Protons provide higher magnification than electrons because of their greater weight (1,840 times that of electrons), which sharply reduces their aberration of diffraction. However, the protons can penetrate a substance only a hundredth as far as electrons. Thus, it is said to be impossible for the protons to pass through the mounting on which the object to be magnified is placed, as do electrons in an electron microscope. Such a mounting would have to be no thicker than one molecule for the protons to pass through. In the proton microscope, therefore, the streams of protons will be reflected at a small angle of incidence from the mounting (rather than be passed through it) and it is this reflection which will be studied.

SCIENCE FEDERATION TO ADMIT NEW MEMBERS

The following is from a letter to the Editor of NUCLEONICS by Robert E. Marshak, chairman of the Federation of American Scientists:

The Federation of American Scientists is now able to announce that provision has been made for admission of members-at-large.

The Federation of American Scientists was formed to integrate those groups of scientists which sprang up spontaneously at the end of the war to alert the public to the implications of the development of atomic energy and to work for sound legislation and policy in this field.

Some of the major activities of the Federation have been (1) providing accurate technical information to the public and to its leaders in order to establish a basis for intelligent social action; (2) mobilizing support for civilian control of atomic energy in this country; (3) supporting the confirmation of the present members of the Atomic Energy Commission; and (4) working for a National Science Foundation. In items (2) and (3), the Federation has been particularly effective.

Scientists have played a prominent part in national affairs in the past two years, and they must continue to fulfill their responsibilities in the future. A few of the subjects under consideration by the membership are the need for more information on the factors involved in biological warfare, the reestablishment of the international scientific community by interchange of scholars, students, and technical information, and the general problem of secrecy in science. What part the Federation will play will be determined by its members. Important policy matters are carefully checked with the membership and decisions must be approved by a large majority.

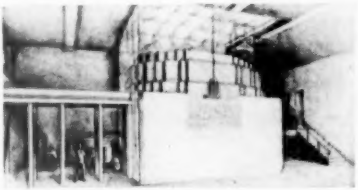
It is recognized that the active participation of many scientists is necessary if the Federation is to be representative and effective. At present there are 2,500 members, most of whom belong to the nineteen local associations. The Federation is anxious to enlarge its membership, especially in the smaller scientific communities and places where groups have not yet been formed.

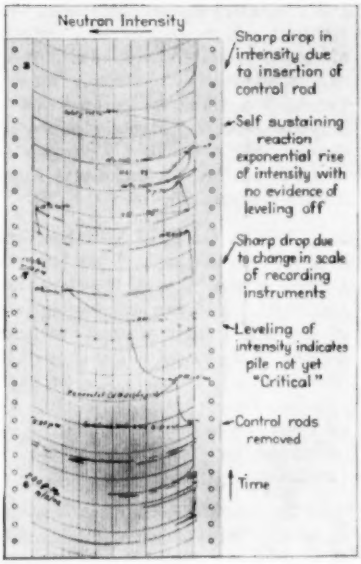
Those who have the equivalent of a bachelor's degree in the natural sciences, mathematics, or engineering, are qualified to become members-at-large, and anyone who is interested in furthering the aims of the Federation is eligible for associate membership-at-large. Dues for members-at-large are set at $5.00 per year; for sustaining members, $10.00; and for patrons, $25.00 or over.

"CHICAGO PILE" ANNIVERSARY COMMEMORATED

Beneath the West Stands of Stagg Field, Chicago, late in the afternoon of December 2, 1942, a small group of scientists witnessed the first self-sustaining nuclear chain reaction system go into operation. This represented the most spectacular culmination of forty-six years of nuclear research.

To commemorate the fifth anniversary of this outstanding scientific achievement, NUCLEONICS presents on these pages the galvanometer record of the event, together with a sketch of the scene that day as preserved by Argonne's staff artist, Melvin A. Miller.




Neutron Intensity
Sharp drop in intensity due to insertion of control rod
Self sustaining reaction exponential rise of intensity with no evidence of leveling off
Sharp drop due to change in scale of recording instruments
Leveling of intensity indicates pile not yet "Critical"
Control rods removed
Time

THE CHICAGO PILE, a layer-on-layer construction of uranium and graphite bricks, was roughly spherical. It was built on a squash court. A balloon cloth bag, as can be seen in the sketch above left, was hung over the pile to remove neutron-capturing air. As additional precaution, a "liquid-control squad" stood on platform above pile to flood it in case three sets of control rods failed. Observers watched from balcony at north end of court. Galvanometer record of Dec. 2, 1942, is now a historic document. Section of record above right shows neutron intensity in pile from about 2:00 p.m. to shut-down. At 2:50 p.m., as control rod came out another foot, counters nearly jammed and pen headed off graph paper. Counting ratios and graph scale had to be changed. Reaction became self-sustaining at 3:28 p.m. When control rod "Zip" entered the pile at 3:53 p.m., it brought to a stop the first chain reaction initiated by man.

Inquiries are cordially invited. They should be sent to the Federation of American Scientists, 1749 L Street, N. W., Washington 6, D. C.

G. E. BUILDS BETATRONS

The National Bureau of Standards has let a contract for a $150,000, 50-million-volt betatron to the General Electric Company. Present schedule calls for its installation in the Bureau's high voltage laboratory this month. The 100-million-volt betatron, to be installed in 1948, will be housed in a special building. This apparatus will serve to carry on radiological studies, made possible by improved instruments for measurements of therapeutic dosages, and general nuclear studies.

NUCLEAR NEWSMAKERS

William F. Meggers, chief of the spectroscopy section of the Bureau of Standards, has been awarded the Frederick Ives Medal of the Optical Society of America for distinguished work in optics.

Shields Warren, pathologist at New England Deaconess Hospital, Boston, and assistant professor of pathology at Harvard, will serve as interim director of the newly created Division of Biology and Medicine of the Atomic Energy Commission. Taking the post on a half-time basis, he will retain his present connections, including his position as director of the Massachusetts State Tumor Diagnosis Service.

R. J. Van de Graaff of MIT has been awarded the Duddell Medal by the Council of the Physical Society (England) for his invention and development of the high-voltage electrostatic generator. **C. F. Powell** of the University of Bristol was awarded the Society's Charles Vernon Boys Prize for his development of the photographic-plate technique for the investigation of fundamental particles.

John K. Gustafson, who has been associated with various mining concerns in the U. S., Canada and Australia since 1930, has been named director of the Atomic Energy Commission's newly established Division of Raw Materials.

Members of the Advisory Committee for Exploration and Mining, recently formed by the Atomic Energy Commission, are **Donald H. McLaughlin, G. Temple Bridgman, Everette L. DeGolyer, Anton Gray, Wilber Judson, R. E. McConnell,** and **Fred Searls, Jr.**

John W. Macy, Jr., special assistant to the manager at the AEC's Los Alamos laboratory, has been appointed director of personnel and organization of the Office of Sante Fe Directed Operations.

L. O. Morgan, formerly with the Manhattan Project at the Universities of Chicago and California and co-discoverer of the element Americium, has been appointed assistant professor in the Department of Chemistry at the University of Texas.

Glenn T. Seaborg, professor in the department of chemistry of the University of California and director of chemistry of the university's Radiation Laboratory, will be awarded the Nichols Medal for 1948 by the American Chemical Society. The presentation will be made at a joint meeting of the New York section of the ACS and the American section of the Society of Chemical Industry on March 5 at the Hotel Pennsylvania in New York. The citation accompanying the award reads:

"Co-discoverer of numerous artificially produced radioactive isotopes and the elements plutonium, americium, and curium. Responsible for the determination of the fissionability of plutonium and other heavy isotopes and major contributor to chemical processes for the production of plutonium. Propounder of the idea of the actinide series for the transuranium elements."

MEETINGS

American Association for the Advancement of Science—Chicago, Ill., Dec. 26–31

American Association of Physics Teachers—17th Annual Meeting, University of Chicago, Chicago, Ill., Dec. 29–31

American Mathematical Society—54th Annual Meeting, University of Georgia, Athens, Ga., Dec. 29–31

American Physical Society—Chicago, Ill., Dec. 29–31

American Institute of Electrical Engineers—Winter General Meeting, William Penn Hotel, Pittsburgh, Pa., Jan. 26–30, 1948

Electrochemical Society—Columbus, O., April 14–17, 1948

American Chemical Society—113th Annual Meeting, Chicago, Ill., April 19–23, 1948

American Association of Petroleum Geologists—Denver, Col., April 26–29, 1948

American Society of Medical Technologists—St. Paul, Minn., June 7–9, 1948

Institute of Radio Engineers—6th Annual Electron Tube Conference, Cornell University, Ithaca, N. Y., June 28, 29, 1948

Growth of the Beryllium Industry

By C. B. SAWYER
President, Brush Beryllium Company
Cleveland, Ohio

IN CONSIDERING the beryllium industry of the present and future from the point of view of economic health, it is well first to analyze quantitatively the history of its ore importations. These are particularly significant since the United States produces less than 10% of the ore it consumes. Consequently, our ore importation is an exceptionally good index of the activity of the beryllium industry.

The only mineral presently constituting a commercial source of the element beryllium is beryl, a beryllium-aluminum silicate derived from granitic veins and containing in ideal composition 14% beryllium oxide, 19% aluminum oxide and 67% silicon oxide. In practice, the beryllium ore based on this mineral will run from about 10 to 12.5% beryllium oxide, averaging perhaps 11.2%, the equivalent of 225 pounds of beryllium oxide per short ton of ore. Imperfect extractions in the plant reduce this figure to about 170 pounds of beryllium oxide per ton of ore actually made available to industry.

During World War II, something approximating 90% of the beryllium oxide extracted from the ore was used for producing alloys of beryllium and copper. The balance of about 10% of the oxide was used principally in the fluorescent lamp industry, but with important portions of this 10% balance going into refractories and light alloys.

The requirement of the fluorescent lamp industry is small compared to the total amount of beryllium oxide handled in the plants extracting it. In other words, only one fifteenth of this country's production of beryllium oxide goes to the fluorescent lamp industry, which is so prominent in health considerations.

Table 1 gives the total amount of ore flowing into the United States, together with domestic production, and indicates the amounts of ore stockpiled and the probable actual plant consumption each year.

Although each short ton of ore con-

TABLE 1

New Beryl Ore Available to United States (Short Tons)

Year	Imports	U. S. mine shipments	Total	End-of-year stockpile	Probable consumption
1937	182	75	257	?	
1938	146	25	171	?	
1939	459	95	554	?	300
1940	805	121	926	(400)?	600
1941	2666	158	2824	2200	1200
1942	2050	269	2319	2002	2300
1943	4840	356	5196	3590	3100
1944	3115	388	3503	4800	2100
1945	1201	39	1240	4587	1200
1946	1181	(50)?	1231	(4000)	1400

tains from 72 to 86 pounds of beryllium metal, it is likely that an average of only 43 pounds of it have actually been recovered as metal by the plants.

The table shows that the beryllium industry began to consume substantial quantities of ore in 1941 and roughly doubled its requirement every war year for three years. Writing in 1940 for *Metals and Alloys*, the author stated that "the ore supply is not unlimited, and were any great demand to appear, the supply might prove temporarily inadequate."

This condition seems to have been reached in 1943 when the world wide efforts of the U. S. Metals Reserve Corporation and other government agencies sufficed to acquire during that year only 5,100 tons of beryl ore at approximately quadruple the prewar price. Present available ore is apparently less. Consequently, the slump in industrial ore requirement after 1943 is a fortunate circumstance if time is required to develop new sources of beryl ore.

Perhaps the new sources will come from ores based on minerals other than beryl, of which many are known; or perhaps they will come from lower grade deposits of beryl itself concentrated by the flotation methods recently developed by the Bureau of Mines. But, as it stands at present, such deposits of ore are unknown and any great industry in beryllium, such as that of tin, must await the location of adequate ore deposits.

Beryllium is thought to lie between tin and arsenic in abundance in the earth's crust and is rated therein as 0.005%.

The beryllium industry in this country really began in 1931 with the estimated consumption of two tons of beryl ore. Only rough figures of ore consumption are available for the succeeding sixteen years, but the temptation to try to reduce them to a formula relating total industrial ore consumption to elapsed years has proven strong. The formula arrived at is:

$$y = 2x^{2.43}$$

where y is the year's consumption of beryl ore in short tons and x is the number of years elapsed beginning with 1931.

The curve resulting from this formula is smooth and of parabolic shape. It does not exhibit the irregularities found in the curve of actual experience but is certainly an approach to averaging out these irregularities or swings. The actual experience curve shows that a particular datum on the formula curve may have to be multiplied or divided by a factor sometimes as great as three to cause it to conform to an irregularity or swing of the experience curve. Great as this factor may seem, it is small compared to the total variation in ore demand over the sixteen years of experience beginning with about two

TABLE 2

Calculated Ore Requirement of Beryllium Industry According to Formula $y = 2x^{2.43}$

Year	*Tons*
1931	2
1932	10.8
1933	29
1934	58
1935	100
1936	156
1937	226
1938	312
1939	420
1940	540
1941	680
1942	840
1943	1040
1944	1240
1945	1440
1946	1700
1947	1940
....	....
....	....
1950	3800

tons in 1931 and ending with 1,700 tons in 1946. This formula indicates that within the above-described factor of three set by experience the United States beryllium industry's ore requirement in 1950 will be about twice that existing in 1947. By contrast, the growth of the industry's ore requirement in each of its early years was several hundred per cent. This simply means that henceforth smaller yearly percentage changes in the size of the industry will result in less abrupt increases in plant exposure of the employees to any toxic effect of beryllium.

Properties of Beryllium

The properties of metallic beryllium or of its compounds are remarkable for the number of extremes which they possess. To illustrate, beryllium is about as light as magnesium but still has a modulus of elasticity greater than that of steel. Although its appearance and chemical stability are similar to aluminum, its melting point is far higher and approaches that of iron. This means that beryllium has the possibility of usefulness at temperatures where aluminum or magnesium would be softened or melted. Beryllium is seventeen times as penetrable as is aluminum and is therefore very suitable for X-ray tube windows. Under nuclear bombardment, it is the most efficient metallic source of neutrons now known.

The strongest, copper-base alloy known is formed with 2% of beryllium and the same is true when nickel is substituted for copper. Magnesium is made relatively non-inflammable by an unbelievably small addition of beryllium (0.005%).

Among its chemical compounds, the oxide of beryllium has the best general properties of any metallic oxide known for making crucibles and electric furnace refractories, but its cost precludes wide usage. Two per cent of beryllium oxide added to zinc silicate broadens its band of fluorescence under ultraviolet light so that it becomes the most valuable phosphor known. Even in the field of physiology, beryllium chemical compounds produce extreme effects.

With so many extreme properties of beryllium and its compounds already revealed, there is every likelihood that the appearance of new ones is only a matter of time. Old uses should continue to enlarge, and new ones putting in appearance will add to the demand for beryllium. Moreover as the metallurgical art surrounding beryllium develops it is likely that some of its defects, such as its brittleness, will be mitigated with resultant broadening of its field of application. The same may be said of its present most important detriment, its high cost. Over a considerable period of time, the beryllium industry will probably become as large as its ore supply can support. As prospecting for beryllium ore has never really become established, particularly for minerals other than beryl, it is likely that new ore finds will appear and widen this fundamental ore base upon which the industry rests.

The use for beryllium now accounting for its greatest poundage is in beryllium copper alloys of which there are two principal compositions. The best known contains approximately 2% of beryllium and is a heat hardenable alloy of great versatility. It is like a super phosphor-bronze, developing strengths in excess of stainless steel and having equal or better corrosion endurance, particularly in the case of brines. It may be purchased from the mill as sheet or wire in a wide range of tempers from the softest to a mill hardened form. All of these are useful for stampings, coil springs, etc., particularly where electrical conductivity, high strength and endurance limit are important.

Where higher electrical conductivity

is desirable, the second type of beryllium copper alloy with about 0.4 per cent of beryllium is employed. It finds particular application in the electric resistance welding field as the actual electrode making contact with the work. Both types of copper alloy are notable for their retention of strength at elevated temperatures. Similarly 2% beryllium nickel is heat hardenable and thereby develops extremely high strengths, some as great as 270,000 psi, which are also retained at elevated temperatures. Owing to difficulties in fabrication, this use has not become widespread. Some stainless steels may be hardened by the addition of 1% beryllium and are capable of retaining their temper at low-red heat.

These examples suffice to establish beryllium as an addition agent of exceptional potency for heat hardening. The effect tends to be general, particularly when the admixture of a third combining element is allowed. Precipitation hardening effects have been noted also in lead and silver. Applications in the die casting field of zinc or aluminum alloys containing beryllium are indicated.

Use as an Alloying Element

An important and growing use for beryllium is as an alloying element added for the purpose of automatically forming films for protecting easily oxidizable elements such as magnesium, aluminum, or zinc in molten alloys. The beryllium in the surface layers of the alloy is quickly oxidized to form a tight strong envelope thereby protecting the bulk from further oxidation. With magnesium, this film is particularly effective but unfortunately grain coarsening caused by such beryllium additions in cast magnesium-base alloys remains. This unsolved problem at present inhibits wider use by the magnesium industry.

The same protective effect is noted in both molten and solid beryllium copper. The effect is probably general and has been observed with silver, even at room temperature, when it tends to reduce tarnishing. Beryllium oxide films have been found to be protective in handling certain nonmolten aluminum alloys at higher temperatures. A possible field for beryllium oxide protective film is in electrical resistance alloys used for heating elements. Beryllium oxide may be actually sprayed on tungsten wires and high temperature alloys for protection at oxidizing temperatures.

Scavenging Effect

Related to the stable oxide film is the scavenging effect of beryllium when added to metals such as copper, nickel and aluminum. It was particularly noted in Germany during the manufacture of intricate castings for aluminum cylinder heads of air-cooled plane motors. The aluminum alloy cleaned up by the scavenging action of beryllium flowed extremely well into the thin sections. Beryllium is therefore interesting as a possible scavenger for aluminum and magnesium casting alloys when used with intricate molds.

When beryllium is considered as a high percentage alloying element for light metals, aluminum with more or less magnesium appears to be substantially the only possibility. Here beryllium is particularly desirable to lend mechanical stability at elevated temperatures, as for pistons in aircraft. Twenty-five per cent of beryllium added to an alloy of the duraluminum type produces interesting properties but has great fabricational difficulties. One of the most outstanding effects of beryllium is upon the modulus of such an alloy which is raised from approximately 10 for aluminum to something in the neighborhood of 17 for the alloy. In addition, the high thermal conductivity of beryllium tends to preserve a high thermal conductivity in the piston

alloy. Where increasing stiffness is required in a light alloy this type may have increasing but limited use.

As already mentioned, pure beryllium is finding increased use for windows in X-ray tubes. This is due partly to its stability at elevated temperatures, partly to its great penetrability to X-rays and partly to increased ability to fabricate. There is the interesting possibility of making a larger portion of the X-ray tube envelope of beryllium, preserving merely enough glass to insulate the high voltage leads.

Mention has already been made of the use of pure beryllium as a source of neutrons in nuclear projects. This use will probably increase because of the great relative stability of beryllium at elevated temperatures under nuclear bombardment.

Acoustical Properties

The high modulus of elasticity of beryllium coupled with its low density produces a velocity of sound in beryllium about twice as great as in steel. In acoustic apparatus, this should be of much importance, as, for instance, in sound radiating surfaces, and generally in the undistorted transmission of vibration. Beryllium-backed optical mirrors, either oscillating or stationary, are similarly an interesting future possibility.

The application of beryllium chemicals has received less commercial attention than of the metal. Outstanding, however, among them is beryllium oxide. Crucibles and electric furnace parts made from it may be used at temperatures 500° C higher than if made from alumina, and in addition have greater strength and resistance to sudden temperature changes. The pure oxide bonds very well and retains a high electrical resistance at high temperatures. The affinity of beryllium for oxygen renders beryllium oxide shapes suitable for high temperature operation where strong reducing conditions exist. Less contamination of melts results from the use of beryllium oxide crucibles. Special applications of refractory shapes in the electric lamp industry may be expected to increase. As in the case of beryllium metal, oxide shapes also may be used as a source of neutrons under nuclear bombardment. In this case the temperature of service may be much higher.

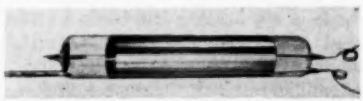
Zinc silicate modified by the addition of 2% of beryllium oxide, fluoresces in a broad band under ultra violet light. It forms the basis of the fluorescent lamp industry, and is supplemented by one or two other fluorescing compounds depending on the color of light desired. The zinc silicate modified by beryllium oxide operates at high efficiency.

Beryllium nitrate is used in the gas mantle industry; beryllium stearate in printing inks; beryllium nitride in making C^{13}.

The beryllium industry has grown from a single application of beryllium oxide to numerous uses nationally of great importance. Much has been accomplished; much more remains to be done. The satisfactory control of the industry's health hazard is a vital part in progress.

GLASS WALL COUNTER

Radiation Counter Laboratories, 1451 E. 57th St., Chicago 37, Ill. This pyrex glass wall counter has been developed for counting radioactive isotopes in the gas phase. The overall length is 14 in., diameter 2 in., and volume approximately 250 cc. Such a volume has been found to be desirable for C^{14} measurements. The counter is long-



term vacuum tested, filled with a counting gas, and then checked. A characteristic curve accompanies each counter, the plateau of which is approximately 200 volts. The unit is flat within statistics.

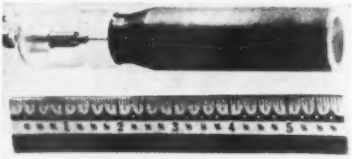
SCALING UNIT

Instrument Development Laboratories, 223 W. Erie St., Chicago 10, Ill. This automatic scaling unit for use with Geiger-Müller counters incorporates facilities for predetermined count and predetermined time operation. A switch allows the selection of 10, 100, or 1,000 times the selected scaling factor

(2, 16, 32, or 64) for any predetermined count. The scaler is designed to automatically shut off after this predetermined number of counts has been recorded, up to a maximum of 64,000 and will indicate the time required for these counts if connected to an electric timer.

GEIGER TUBE

North American Philips Co., Inc., 100 E. 42nd St., New York 17, N. Y. A multipurpose, self-quenching Geiger tube for use with beta, gamma and soft X-radiation has been developed. Overall length of the new Geiger tube is 6 in., diameter is 1 in. The length of the metal cathode is 3¾ in. The anode is 4⅛ in. long and bears a glass bead at its free end. With a mica window which averages approximately 3.2 milligrams per square centimeter,



the tube is claimed to be useful for tracer work employing C^{14}, for soft X-radiation and for operations involving radium. Used with suitable circuits, it is designed to handle in excess of 3,000 discrete counts per second. Threshold voltage is 1350 and the plateau exceeds 300 volts in length. Normal operating potential is 1450. Laboratory tests indicate that this tube will have a life exceeding 10^9 counts. Quantum efficiency for soft X-rays is in the order of 70–80%.

GAMMA-RAY LEVEL INDICATOR

Engineering Laboratories, Inc., 624 E. Fourth St., Tulsa 3, Oklahoma. The Gagetron is an electronic instrument for liquid level indication and control. It uses a gamma-ray detector and the penetrating power of gamma rays emanating from a small radium source to determine liquid level without any connections originating inside the containing vessel. In operation, a gamma-ray source is placed in a float in the liquid. The radiations strike an external counter, which is connected to a circuit that converts the incoming pulses into a height reading.

ALL-METAL GEIGER TUBE

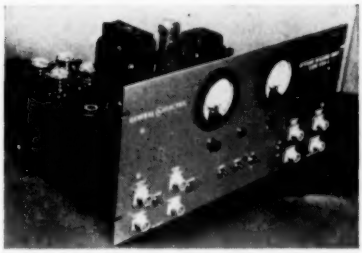
Geophysical Instrument Co., 1820 N. Nash St., Arlington, Va. The active diameter of this all-metal Geiger-Müller tube is very nearly equal to the overall outside diameter; consequently, it is claimed to be particularly adapted for use in cosmic ray telescopes and other coincidence circuit arrangements. The operating voltage is in the vicinity of 1000 volts and the tube has a cosmic

ray efficiency which is claimed to be better than 99%. The plateau is 100 volts or more and the change in counting rate over this plateau is guaranteed to be kept within 0.05% per volt. Tubes are furnished separately for those constructing their own apparatus or are supplied complete with auxiliary

systems, ready for measurement of gamma- and cosmic-ray intensities. Special tubes with thin windows are available for measurement of less highly penetrating rays.

DECADE SCALER

General Electric Co., Electronics Division, Syracuse, N. Y. This unit is a two-channel, decade scaler. Each



channel of the scaler is designed to count up to ten individual input voltage pulses of extremely short duration and separation, indicate the exact number counted, and deliver one output voltage pulse for every ten input pulses. The scaler will then automatically reset itself to zero and repeat the process, the input pulses being either entirely random with respect to time, or periodic and continuous. By operation of a toggle switch, scale of 100 is obtained.

THE FACT THAT NEUTRONS can give rise to interference effects is an obvious consequence of the wave properties of matter. The effects of neutron interference have shown themselves in a number of experiments. A classic example is embodied in the work on the scattering of neutrons by para and orthohydrogen as a function of average neutron energy. The diffraction of neutrons by crystals was first reported to be observed with cyclotron-produced neutrons slowed down in paraffin. The neutron intensities obtainable in this way were presumably just sufficient to demonstrate the effect.

The development of chain reacting piles has now given us sources of neutrons of sufficient intensity to put neutron diffraction in a category comparable with that of X-ray diffraction. One of the first applications of the diffraction of neutrons by crystals was in the study of low energy resonance absorption levels. Work along this line has been carried on simultaneously since 1945 at Clinton Laboratories and at the Argonne Laboratory. —*Phys. Rev.* **72,** 109 (1947)

ABSTRACTS

CHEMICAL PUBLICATIONS

The growth of La^{140} (40 hours) from Ba^{140} (12.7 days), W. E. Grummitt, J. Guéron, G. Wilkinson, L. Yaffe, *Can. J. Research*, **25B**, 357–363 (1947). The growth of the La^{140} daughter from the Ba^{140} parent, which was obtained from neutron-bombarded uranium, was studied and compared with the growth calculated from the radioactive dependence laws. The ratio of the observed growth of La^{140} to the calculated growth was found to be 1.3, probably because of the existence in the Ba^{140} radiation of soft electrons which escaped detection in the counting arrangement used. The data show that, in comparing the activities of different beta emitters, there is a danger in the use of corrections obtained by extrapolation of self-weakening and external absorption data. It is essential to use the thinnest possible samples both in actual measurements and in establishing the preliminary correction curves; this is particularly true in the case of emitters with complex spectra.

The fission yields of Ba^{139} and Ba^{140} in neutron fission of U^{235} and U^{238}, W. E. Grummitt, J. Guéron, G. Wilkinson, L. Yaffe, *Can. J. Research*, **25B**, 364–369 (1947). Using natural uranium, the fission yields of Ba^{139} and Ba^{140} for thermal neutron fission of U^{235} and fast fission of U^{238} were measured by comparing the barium fission product activities with the U^{239} formed in radiative capture. Since the beta activities produced both by capture and by fission are proportional to the respective cross sections for these processes, the fission yields can be calculated. The observed values are 6.1% and 5.6% for Ba^{139} and Ba^{140}, respectively, for thermal fission, and 5.1% and 4.2% for Ba^{139} and Ba^{140}, respectively, for fast fission. Resonance fission cannot contribute more than 5% of the observed thermal fission.

Fission yields of masses 131, 132, 134, and 136 formed in neutron fission of uranium, L. Yaffe, C. E. Mackintosh, *Can. J. Research*, **25B**, 371–375 (1947). Using the previously determined value for the fission yield of Ba^{140}, the fission yield of I^{131} (8.0 days) in neutron fission of uranium was calculated to be 5.75×10^{-3} from the experimentally determined ratio of I^{131} to Ba^{140}. From this, yields were assigned to the 132, 134, and 136 chains using the known relative abundance values for these chains. A mass of 134 was assigned to the unidentified chain containing the 54-min I.

The gamma-ray measurement of radium ore concentrates, W. J. Hushley, W. R. Dixon, *Can. J. Research*, **25A**, 210–222 (1947). A method is described for measuring the radium content of samples in the order of micrograms of radium per gram of material. In order to obtain a radiation intensity convenient to measure, a few hundred grams of material are required, and for such bulk sources absorption corrections as high as 30% may be necessary. The method comprises measuring the radiation equivalent of the source, as found by comparing the intensity of γ radiation from it with that from a standard radium capsule, and correcting for self-absorption made on the basis of an absorption coefficient measured with the capsule touching the center of the back face of the bulk source. The radium content was determined with an error of less than 2% for the ores studied. γ-ray activities were measured by Geiger-Müller counters. Effect of radiation scattered by the source into the detector is discussed.

New photographic emulsions showing improved tracks of ionizing particles, P. Demers, *Can. J. Research*, **25A,** 223–251 (1947). New emulsions have been prepared that have very small grain size and grain spacing. In these emulsions the tracks of ionizing particles consist of grains of diameter $\sim 0.2\mu$, which often form continuous lines. The standard deviation in determining energy from a single measurement of range is 3.25 to 3.5% for protons of 0.6 to 2.4 Mev, and 1.3 to 1.9% for α-rays of 4 to 8.5 Mev. The tracks of different particles, especially protons, can be more easily distinguished from each other. Slow electron tracks have occasionally been seen. The actions of certain sensitizing and desensitizing substances are discussed, and a quantitative theory is advanced for the probability of development in terms of the specific energy loss and a sensitivity parameter of the emulsion.

A method for computing transformations in radioactive series, W. H. Watson, *Can. J. Research*, **25A,** 252–260 (1947). The coefficients of the exponential terms in the expressions for the time dependence of the amounts of the various products in a radioactive series can be obtained by a direct procedure using matrix representation. The method involves partition of a matrix which can be written down directly from the diagram of the series. An example involving double branching with 10 members of the series is discussed.

Ratio of neutron absorption cross sections of boron and hydrogen, W. J. Whitehouse, G. A. R. Graham, *Can. J. Research*, **25A,** 261–275 (1947). The ratio of the neutron absorption cross sections of boron and hydrogen was found to be 2270 with a statistical error of ± 30. The integration method, with a small BF_3 chamber as detector, was used. Measurements were made first in distilled water and then in a dilute boric-acid solution. The systematic error that might exist because of perturbation by the BF_3 chamber of the neutron density was shown to be less than 3%, if it exists.

A theorem on neutron multiplication, G. Placzek, G. Volkoff, *Can. J. Research*, **25A,** 276–292 (1947). A study was made of the behavior far from a source of the neutron distribution in an infinite homogeneous medium in which a convergent chain reaction (multiplication factor $k < 1$) takes place. Under very general assumptions, at large distances r from the point source the neutron distribution always has the form $A/r \exp(-\mu r)$, where μ and A are constants which can be expressed in terms of the Fourier transform of the spacial distribution of primary fission neutrons.

Nuclear transformations in the new high-energy ranges, G. T. Seaborg, *Chem. Eng. News*, **25,** 2819–2822 (1947). An address by Seaborg. The types of new high-energy accelerators (100–400 Mev) and the results already achieved with them, and those hoped for, are discussed.

Production of radioactive carbon monoxide from barium carbonate, J. T. Kummer, *J. Amer. Chem. Soc.*, **69,** 2239 (1947). $C^{14}O$ can be conveniently prepared by exchanging the C^* in a small quantity of C^*O_2, obtained from BaC^*O_3 of high specific activity, with the carbon in a large amount of CO. The exchange is carried out over the hot tungsten filament of an ordinary light bulb, and is complete in about 16 hours. Details of the high vacuum system employed are given.

The halogen-metal interconversion reaction and its application to the synthesis of nicotinic acid labeled with isotopic carbon, A. Murray, III, W. W.

Foreman, W. Langham, *Science*, **106**, 277 (1947). Prepared from *n*-butyl lithium and 3-bromopyridine, 3-pyridye lithium was carbonated with both $C^{13}O_2$ and $C^{14}O_2$ to yield isotope-labeled nicotinic acid. A reaction using 21 millimoles of $BaC^{13}O_3$ gave an 82% crude yield of nicotinic acid having a C^{13} content of 0.9 isotopic per cent.

The synthesis of lauric acid and dodecylamine containing carbon-14, H. J. Harwood, A. W. Ralston, *J. Org. Chem.*, **12,** 740–741 (1947). $C^{14}O_2$, obtained from BaC^*O_3, was reacted with undecylmagnesium bromide to give radioactive lauric acid. The latter was converted to the nitrile by passage over aluminum oxide in the presence of ammonia. Reduction of the nitrile with sodium gave radioactive dodecylamine which was isolated as the acetate. Successive addition of inert materials at each step of the synthesis reduced losses of active compounds and gave desired activity of final products.

. . . I. W. RUDERMAN

LIFE SCIENCE PUBLICATIONS

Cobalt in metabolism studies: IV. Tissue distribution of radioactive cobalt administered to rabbits, swine, and young calves, C. Comar, G. Davis, *J. Biol. Chem.* **170,** 379–389 (1947). Cobalt chloride containing radioactive cobalt was administered to bull calves orally and by jugular injection. The animals were slaughtered and the various tissues and organs analyzed for isotopic cobalt. The radioactive cobalt distribution in the tissues of the injected calf was similar to that of previously reported adult animals. It was found that the young calf absorbed a greater percentage of the orally administered cobalt than did the older animals. The tissue distribution of the orally administered cobalt was the same as the injected cobalt.

Similar data on swine, rabbits and cattle revealed no variations in regard to internal metabolism of cobalt. The view that the major function of cobalt in the ruminant is localized in the rumen is supported by the present findings, but the possibility of hematopoietic function is not excluded.

Uptake of radioactive iodine by the normal and disordered thyroid gland in children, E. Quimby, D. McCune, *Radiology* **49,** 201–204 (1947). Radioactive iodine I^{131} in the form of a dilute solution of sodium iodide was administered orally to 54 subjects including infants and children ranging in age from 1–14 years. Many controls were included. The concentration and retention of I^{131} in the thyroid gland varied from 12% in those without evident thyroid disorders to several times this value in hyperthyroids. Hypothyroid cases had less than 1%. Some low values were also found in normal thyroid cases. This variability limits interpretation of I^{131} level, but it is suggested that more clean-cut results could be obtained by more careful standardization with respect to patient's state of health and previous iodine intake.

Preparation of radioautographs of thyroid tumors for study at high magnifications, T. Evans, *Radiology* **49,** 206–213 (1947). Direct mounting of tissue sections on photographic emulsions results in the production of radioautographs which are in alignment with histologic preparation. Five plates are shown.

The halogen-metal interconversion reaction and its application to the synthesis of nicotinic acid labeled with isotopic carbon, A. Murray, III, W. Foreman, W. Langham, *Science* **106,** 277 (1947). Essentially the reaction is a double decomposition between an organoalkali metal compound and an aryl halide. The extremely short reac-

tion time permits the formation of organometallic compounds having other reactive groups, which is not possible when the Grignard reaction is employed.

N-butyl lithium and 3-bromopyridine were reacted to give 3-pyridyl lithium. This compound was reacted with $C^{13}O_2$ giving an 82% crude yield of nicotinic acid containing 0.9 isotopic %. The reaction was repeated using $C^{14}O_2$ resulting in a yield of 62% nicotinic acid with a specific activity of 8 microcuries per mg. In a similar type of reaction *p*-aminobenzoic acid was prepared in 21% yield.

The use of C^{13} and C^{14} in medical research, D. Wilson, *J. Franklin Inst.* **244,** 209–219 (1947). A review briefly tracing development of the isotope technique. Methods of preparation of C^{13} and C^{14} are described. The methods of analysis of the carbon isotopes are briefly discussed. Experiments carried out in the author's laboratory, notably uric-acid formation which involved the feeding of tagged compounds to pigeons, are presented in some detail.

The conversion of thiocyanate sulfur to sulfate in the white rat, J. Wood, E. Williams, Jr., N. Kingsland, *J. Biol. Chem.* **170,** 251–259 (1947) Potassium thiocyanate prepared from barium sulfate containing radioactive sulfur was administered by intraperitoneal injection to rats. Urine was collected and analyzed for sulfate and thiocyanate ions. It was found that between 1 and 4.5% of the injected thiocyanate radioactive sulfur appeared as sulfate, but the major part was excreted unchanged. A number of possibilities of thiocyanate to sulfur conversion in the animal body and excreta are discussed.

No radioactive sulfur was found in the muscles, adrenals or thyroids after 20 or 25 days. None was found in the bones after 20 days. Feces accounted for about 5% of the injected thiocyanate sulfur. A method of determining very small quantities of isotopic thiocyanate in the urine is presented.

Radioactive phosphorus, P^{32}; A six-year clinical evaluation of internal radiation therapy, C. Doan, B. Wiseman, C. Wright, J. Geyer, W. Meyers, J. Meyers, *J. Lab. Clin. Med.* **32,** 943–969 (1947). An analysis of the results in the treatment of 100 patients with radioactive phosphorus is presented. Among the diseases reported on are polycythemia rubra vera, lymphatic, myelogenous and monocytic leucemias, Hodgkin's Syndrome, metastatic carcinoma and sarcoma and multiple myeloma. Radioactive phosphorus was of greatest value in controlling the clinical and hematologic manifestations of polycythemia rubra vera. P^{32} was found to be a valuable adjunct to other therapy in some of the more chronic leucemic states. Only occasional brief favorable effects occurred with the use of radioactive phosphorus in the acute leucemias. Hodgkin's Syndrome could not be controlled by this therapy.

It is emphasized that the effectiveness of the method depends upon "selective" cell structure. Wide variance in individual susceptibility and tissue response has been found. Dosage must be adjusted individually. Administration of small well-spaced doses of P^{32} with frequent and complete blood and bone-marrow studies are suggested to insure normal hematopoiesis. Twelve pages of tables of case histories and eighteen references are included.

Physiological availability of iodine in dithymol diiodide, R. Baldwin, R. Thiessen, Jr., E. McInroy, *Science* **106,** 317–319 (1947). Dithymol diiodide was synthesized from potassium iodide containing I^{131} and fed to three pairs of albino rats. One pair was fed a normal diet including dithymol diiodide corresponding to 0.007% iodine

and the second pair received 100 times as much or 0.7% iodine along with a normal diet. The third pair was fed a normal diet, but each was given three oral administrations by syringe of a suspension of dithymoldiiodide in water.

At the end of a 36-hour feeding period the thyroid, kidney, liver and spleen were removed from each rat and were used to prepare radioautographs. It was estimated that from 25 to 50% of the iodine consumed was concentrated in the thyroid. The thyroids of rats given the diet with 100 times the normal amount accumulated more iodine than those of the rats given much larger doses orally. This is believed due to a greater percentage of excretion of the compound in the feces of the rats given oral doses. Not enough radioactive iodine appeared in the kidney, liver and spleen to produce radioautographs.

The metabolism of L-histidine, C. Tesar, D. Rittenberg, *J. Biol. Chem.* **170,** 35–53 (1947). The metabolic fate of L-histidine was studied. Synthetic L-histidine containing excess N^{15} in the γ-nitrogen of the imidazole ring was added to the stock diet given to adult rats for 3 days. During this period, feces and urine were collected; they accounted for 3% and 42%, respectively, of the administered N^{15}. The rats were killed and their bodies divided into four portions; skin, liver, other internal organs and carcass. The isotope concentration of the components of each portion was then determined. Blood plasma and liver proteins contained the highest N^{15} concentration, whereas the skin, internal organs, erythrocyte proteins and muscle had relatively low N^{15} concentrations.

Compared to urea, the isotope concentration of urinary ammonia was lower than in those experiments in which the isotope was located in the α-amino nitrogen of the administered amino acids.

The minimal replacement of histidine in the liver was 29%, in the carcass 8% and in the erythrocytes 3% during the experimental period. Of the total isotope in the organs, 49% of liver N^{15} and 57% of carcass isotope were present in the replaced histidine.

From the relative isotope concentrations of the various isolated components, it is believed that the imidazole nitrogen is redistributed in a manner similar to that of ammonium salts. There was no evidence that histidine is the precursor of glutamic acid, arginine, creatine or purines. Histidine nitrogen concentration in liver protein nitrogen was found to be 5.2% and 4% for carcass proteins.

The turnover of phosphate in the pineal body compared with that in other parts of the brain, U. Borell, A. Orstrom, *Biochem. J.* **43,** 398-403 (1947). Rats were injected intraperitoneally with a solution of radioactive phosphorus (as sodium phosphate) containing 5% glucose. After 40 minutes the animals were decapitated, blood samples drawn, and parts of the brain dissected for radioactivity analysis. The greatest activity was found in the pineal body which was 3–4 times higher than that of the pituitary gland and choroid plexus. The remaining portions of the brain had low activity. The high activity of the pineal body was also found in a number of other animals.

All parts of the brain had a higher activity at 40 min after radioactive phosphorus injection than at 145 min or at 24 hr later. High phosphate turnover in the pineal body was not caused by the blood in the organ. Radioactive P in the pineal takes part in a rapid turnover in which P^{32} enters into carbohydrate phosphate esters. The pineal radioactive P also reacts slowly to form phospholipids and nucleic acids.

. . . BERNARD KANNER

PHYSICAL PUBLICATIONS

High resolving power, curved-crystal focusing spectrometer for short wave length X-rays and gamma rays, J. DuMond, *Rev. Sci. Instr.* **18,** 626–638 (1947). The spectrometer uses the (310) planes of quartz, in a plate curved to a radius of 2 meters. The solid angle subtended at the focus is 0.00025 sterradians, giving quite high intensity. The resolution is such that rays of a given wave length are focused to within 0.06 mm, and the dispersion 1.186 x-units per mm at short wave lengths.

Counter for use in scattering and disintegration experiments, P. Koontz, T. Hall, *Rev. Sci. Instr.*, **18,** 643–646 (1947). This article describes a chamber which can be used either as an ionization chamber or proportional counter, utilizing protons or alphas from disintegrations, or recoils in the case of direct counting of neutrons or their scattering. The chamber is used with an amplifier and preamplifier, and is provided with a discriminator. Neutrons from a few kev to a few hundred kev can be measured. The resolution is not exactly known, since the reactions investigated do not have known line widths.

Total cross section of aluminum for fast neutrons, I. Seagondollar, H. Barschall, *Phys. Rev.*, **72,** 439–444 (1947). The cross section was measured as a function of energy of the neutrons from 10 to 100 kev. The neutrons were obtained from the Li(p,n) reaction, the protons being accelerated by an electrostatic generator; the scatterers were aluminum disks, and the neutrons were detected in a proportional counter filled with BF_3. Ten resonances were observed, and a drop in cross section just before the first may correspond to Weisskopf's prediction from his theory of neutron scattering.

An upper limit for the cross section for scattering of neutrinos by hydrogen, E. Wollan, *Phys. Rev.*, **72,** 445–446 (1947). This experiment used a hydrogen-filled counter to determine an upper limit to the scattering cross section of neutrinos on hydrogen. Calibration of the ionization chamber was made with a Ra-Be source, and the flux of neutrinos obtained from a pile, assuming two neutrinos per fission. On the basis of the ionization produced, the upper limit of the cross section was established at 2×10^{-30} cm^2.

Alpha particles associated with fission, E. Wollan, C. Moak, R. Sawyer, *Phys. Rev.*, **72,** 447–451 (1947). Twenty long-range particles associated with fission have been observed in photographic emulsions. The grain spacing leads to the conclusion that they are probably alpha particles, with maximum range 40 cm of air, and energies from 9 to 22 Mev. Evidence that the alphas are liberated during fission, being pinched off between two heavier fragments, is found in the angular distribution of the alphas.

The relative abundance of some light nuclear species as determined from the composition of stony meteorites, H. Brown, C. Patterson, *Phys. Rev.*, **72,** 456–457 (1947). Certain elements are found in silicate phases almost entirely. Combining the relative abundances of such nuclei in stony meteorites and using known isotopic abundance ratios, relative abundances of certain isobaric pairs have been calculated.

On the rise of the wire-potential in counters, S. Korff, *Phys. Rev.*, **72,** 477–481 (1947). The process of the rise of voltage on the wire as a function of time when an electron is collected is investigated theoretically. The confirming results are applied to the problem of high counting rates.

A new method of separation of the isotopes He^3 and He^4, J. Daunt *et al.*, *Phys. Rev.*, **72,** 502–505 (1947). This separation is accomplished by cooling to a very low temperature. He^3 does not take part in the superflow, and is left behind in greater concentration when He^4 flows out of the vessel.

On the two-meson hypothesis, R. Marshak, H. Bethe, *Phys. Rev.*, **72,** 506–509 (1947). To explain the high production rate of mesons, together with their subsequent weak interaction with matter, the theory is proposed that there are in nature two kinds of mesons. The heavy kind, recently observed in photographic emulsions in England, would, according to this theory, be produced in large numbers in the upper atmosphere by the primary cosmic radiation and are responsible for nuclear forces; these heavy mesons subsequently decay into the lighter ones that are found normally and have weak interaction with matter. The lifetime of the heavy meson is estimated at 10^{-8} to 10^{-12} sec. The spin of the heavy meson is not conclusively established.

Studies of the delayed neutrons, A. Snell, V. Nedzel, *et al.*, *Phys. Rev.*, **72,** 541–544 (1947). The experiment consisted of bombardment of U_3O_8 with neutrons from a cyclotron. These neutrons had to pass through a block of graphite to reach the uranium. They caused fissions in it whose neutrons were registered by a BF_3 counter. Decay curves with half-lives of 0.4, 1.8, 4.4, 23, and 56 sec with relative initial intensities of 0.4, 0.5, 1.1, 1.0, and 0.14, were found. Total initial delayed-neutron intensity was about 1% of instantaneous fission-neutron intensity.

Studies of the delayed neutrons II, A. Snell, J. Levinger, *et al.*, *Phys. Rev.* **72,** 545–549 (1947). The chemical isolation of the 23- and 56-sec activities was achieved by bombarding uranyl nitrate solutions with neutrons and testing quickly for various elements. The 23-sec activity was found to follow iodine and the 56-sec activity bromine chemistry. The half-lives indicate that the probable reaction is beta decay of Br^{87} and I^{137} into Kr^{87} and Xe^{137}, which then emit a neutron each and become stable Kr^{86} and Xe^{136}. Delayed neutrons from thorium fission were also investigated.

Delayed neutrons from Pu^{239}, F. de Hoffman, B. T. Feld, *Phys. Rev.*, **72,** 567–569 (1947). The experiment was performed by irradiating samples of U^{235} and Pu^{239} in a graphite column, then removing them and placing them in a flat parallel-plate U^{235} fission chamber acting as a detector. The time required was 2 sec, some runs being made with a 5-sec delay. The shapes of the decay curves are very similar. The ratio of delayed neutrons from Pu^{239} to those from U^{235} is found to be 0.47 for 2-sec runs and 0.40 for 5-sec runs. This would indicate more short-period delayed neutrons from Pu^{239}, but the experimental and statistical errors are large enough so that this conclusion cannot be drawn.

Delayed neutrons in plutonium and uranium fission, W. Redman, D. Saxon, *Phys. Rev.*, **72,** 570–575 (1947). The method in these experiments involved removal of the sample in order to determine counts from delayed neutrons. The time of withdrawal was reduced to 0.6 sec to make the results for shorter lifetime activities more accurate. The samples were irradiated in the Argonne graphite pile. The results indicate substantially the same periods for Pu^{239} and U^{235}; therefore, they are probably associated with the same fission fragments. The lifetimes involved were found to be 55, 22.5, 4.45, and 1.10 sec.

The scattering of slow neutrons by bound protons. III. Intermediate energies, P. Zilsel, B. Darling, G. Breit,

Phys. Rev., **72**, 576–580 (1947). This paper derives the scattering cross section on protons elastically bound in molecules for neutrons of energy greater than zero but less than that required to excite a molecular level. Fermi's approximation is found to be accurate to within 0.3% for a number of energies and angles of scattering calculated from the corrected expression.

Gamma radiation from tantalum, iridium, and gold, J. M. Cork, *Phys. Rev.*, **72**, 581–585 (1947). The beta spectra of various elements was investigated photographically using semicircular focusing magnetic spectrometers. Nuclear level schemes for residual nuclei following beta emission are deduced from the gamma-ray energies.

Neutron cross-section studies with the rotating shutter mechanism, T. Brill, H. V. Lichtenberger, *Phys. Rev.*, **72**, 585–590 (1947). A rotating shutter provides bursts of neutrons which reach a BF_3 counter after passing through a sample. Gate circuits allow simultaneous measurements to be taken on six velocity intervals, by counting at various times after the shutter has begun to rotate. The circuits are activated by photoelectric cells, on which falls the light reflected from a mirror mounted on the shutter. This mirror is also used to count the speed of shutter rotation. Gold, gadolinium, and dysprosium were investigated, and cross sections given.

Energy and half-life of the Be^{10} radioactivity, E. McMillan, *Phys. Rev.*, **72**, 591–593 (1947). An absorption curve was taken using Al absorbers. Residual counts beyond the end point are of the order to be expected from X-rays generated from stoppage of electrons in sample and absorber. The upper-limit energy corresponding to the range obtained from the absorption curve is 560 (±10) kev. The half-life is obtained from the isotopic abundance ratio of Be^{10} to Be^{9} and the specific activity and is found to be $(2.5 \pm 0.5) \times 10^{6}$ years.

The discharge mechanism of self-quenching Geiger-Müller counters, S. H. Liebson, *Phys. Rev.*, **72**, 602–608 (1947). A split counter arrangement was used to determine the absorption coefficient for the photons which cause the spread of the discharge along the wire. Plots of the probability of propagation for various distances and voltages are given. Argon and either methylene bromide or ethyl alcohol at various pressures were used to fill the counter. The vapor dissipates electron energy, reducing the number of photons produced; the absorption coefficient depends only on the argon.

Interaction of neutrons with electrons in lead, W. Havens, I. Rabi, L. J. Rainwater, *Phys. Rev.*, **72**, 634–636 (1947). To find the interaction between neutrons and electrons, the cross section of liquid lead for neutrons as a function of energy was measured on the Columbia neutron velocity spectrometer. Lead is suitable because of its lack of resonances in the slow-neutron region; by using a liquid, any solid diffraction effects are avoided. By subtracting the zero-energy cross section and a parabolic correction for liquid diffraction effects similar to that encountered in X-rays, the cross section remaining is due to the electron-neutron interaction. The results are consistent with an attractive potential well of 2500 ev, which agrees in sign with the result predicted by meson theory.

Isotopes of greatest abundance, M. Levitskaya, *Comptes rend acad. sci. U.R.S.S.* **55**, 395–398 (1947). A table of isotopes is given and leads to the conclusion that a nucleus which does not coincide with any of the stable isotopes is positron- or electron-emitting, according as its number of neutrons is smaller or larger than that in the nucleus of

greatest abundance [for the same Z (atomic number)]. For smaller Z, there must exist, in order for this rule to hold, a stable isobar of number $Z - 1$ or $Z + 1$, respectively.

Study of atmospheric showers, A. Alichanian, T. Asatiani, G. Muskhelishilli, *J. Phys. U.S.S.R.* **11,** 16–22 (1947). Showers much narrower in area covered than Auger showers have been recorded. They are more frequent, but contain fewer particles. An upper limit for particle density in narrow showers is set at 100 particles per square meter. There also are found to exist wide penetrating showers of very high density.

Resonance phenomena in the elastic scattering of photoneutrons with energies of 0.1, 0.2, 0.3, and 0.4 Mev by atomic nuclei, T. Goloborodko, *J. Phys. U.S.S.R.* **11,** 44–48 (1947). Variation with energy of cross section of neutrons on nuclei in these results indicated energy levels separated by intervals of the order of 100 kev for both heavy and light nuclei. The explanation is proposed that the surface layer of all nuclei consists of structures having the constitution of alpha particles.

Les équations d'ondes du second ordre dans la théorie du meson, G. Petiau, *J. phys. radium,* **8,** 116–122 (1947). Equations for the behavior of a meson of spin 1 in an electromagnetic field are investigated. The magneton corresponding to the meson is found to be 0 or $\pm \frac{h_e}{2\pi m_0 c}$

Experiments in multiple-gap linear acceleration of electrons, W. Allen, J. Symonds, *Proc. Phys. Soc., London,* **59,** 622–629 (1947). A linear accelerator of three accelerating stages was used to accelerate electrons to 0.85 Mev, using a 10.0-cm magnetron which delivered 300 kw. Focusing problems are not extensively discussed.

The acceleration of charged particles to very high energies, M. Oliphant, J. Gooden, G. Hide, *Proc. Phys. Soc., London,* **59,** 666–677 (1947). To reveal more experimental information about nuclear binding forces, protons of 1-Bev energy are desirable. A brief discussion of relative advantages of various accelerators, both for light and heavy particles, is followed by the proposed design of a 1.3-Bev synchrotron for proton acceleration. An iron-core magnet is to be used. The time of acceleration is to be about 1 sec, with an injection energy of 300 kev. The magnetic field is to increase approximately linearly and the frequency change simultaneously from 0.27 to 9.5 Mc. Part of this variation is to be obtained by a tuned circuit of low Q, and the remainder by mechanical tuning.

A rubber vacuum chamber stretched over a metal frame is proposed. The protons are to be brought out of the chamber by a deflecting voltage applied to a long electrode in a time which is long compared to the time for one revolution (10^{-7} sec). This is to be done by a large capacity connected to a spark gap, set so as to be applied at the end of the accelerating cycle. The cost is estimated at £100,000, while that of a similar machine of 10 Bev is set at £10,000,000 ($40,000,000).

Theory of the proton synchrotron, J. Gooden, H. Jensen, J. Symonds, *Proc. Phys. Soc., London,* **59,** 677–693 (1947). This paper is primarily concerned with the increased problems of phase oscillations in a synchrotron for heavy particles. In the region below that of relativistic velocities, the motion is not inherently stable, the phase oscillations being undamped to a first approximation. Factors affecting the amplitude of phase oscillation are eight in number. Since four are subject to external control, it is concluded that proton acceleration in such a machine is possible with reasonable care.

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